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INTERPLANETARY SPACEFLIGHT MISSIONS

Theodor Ginzburg

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Theodor Ginzburg, Zürich

ABSTRACT. The Deutsche Gesellschaft für Raketentechnik und Raumfahrt (German Association for Rocket Engineering and Space Travel) has taken on the task of holding three symposia each year on current problems of space travel. The last symposium of last year, which took place on 7 December in Munich and in which about 150 scientists from industry and research took part, was dedicated to the theme "Interplanetary Spaceflight Missions." The experts reported for the most part on research programs being carried out by the firms of Bölkow and Erno in cooperation with NASA. Two projects are in the foreground of the investigations: first the solar probe, which is being planned as a cooperative German-American effort for the seventies, and second a spaceflight mission to Jupiter, which, besides observing the planet, will among other things take measurements within the heretofore scarcely explored asteroid belt. This Jupiter probe is expected to be outfitted and launched jointly by American and European space agencies. -- A number of presentations were also devoted to the so-called swing-by technique, which permits the use of the gravitational field of a planet in altering the orbit of a passing space vehicle. The possibility exists that in the future with the aid of this method interplanetary flights may be made outside the plane of the ecliptic, a thing which could not be realized with the propulsion systems previously available. -- All in all, the work of the German research groups offers the beginning of an actual expansion (not just an imitation) of the American space program. The first step could thus be taken in the direction of a coordinated international program, in which Europe can play a part in keeping with her scientific capacity. /9*

I. Exploration of the Solar System

An essential part of the scientific program connected with space travel is directed toward the exploration of the solar system, with its planets, planetoids, moons, and interstellar matter. As early as 1960 the Russians started the race to our neighboring planets with the launching of two Mars probes, which, to be sure, were failures. Since that time, year after year, whenever the planets were in favorable positions, the Russians as well as the Americans have sent out probes to Mars and Venus, only a few of which, however, have fully satisfied the expectations entertained for them. The Americans were first to be successful, when their *Mariner 2* succeeded in a fly-by of Venus, passing within 35,000 km of that planet; many surprising scientific facts about the atmosphere of Venus were learned from measurements taken at that time and

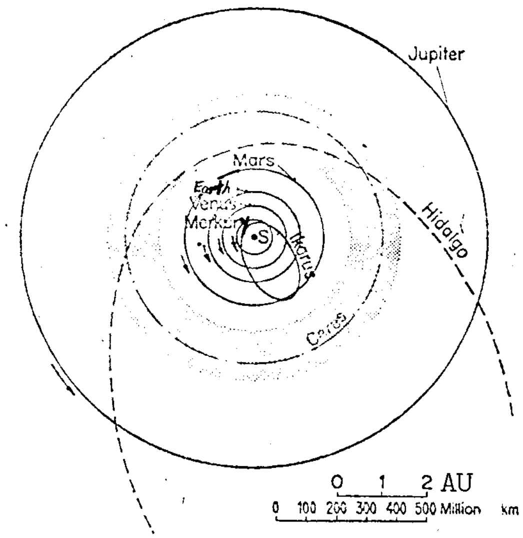
*Numbers in the margin indicate pagination in the foreign text.

analysis of the orbital elements. After the failure of *Mariner 3*, the first American Mars probe, *Mariner 4* succeeded in flying by Mars at a distance of 9,844 km, 228 days after its launching on 14 July 1965. Within 26 minutes 22 pictures were taken and stored, which were later transmitted to the earth over a distance of more than 300 million km in the course of a few weeks, and which could be received here without difficulty. These first pictures of Mars surprisingly showed a cratered landscape similar to that of the moon, and the phantasy of the Martian canals, which for decades had lent wings to man's imagination, resolved itself under optimum optical conditions into individual craters and spots.

The string of Russian successes began, after many misses, early in 1966, when the probe *Venus 2* passed the planet at a distance of 24,000 km, while a few days later a second Venus probe burned out in the planetary atmosphere, or may even have landed on the surface. Finally, during the past year a great splash was made by the successful landing of the instrument package of a Russian Venus probe, which was dropped by parachute, entered the atmosphere of Venus, and was able to land there. In the shadow of this great accomplishment, the results of the American Venus probe, which made a practically simultaneous fly-by of that planet and which also provided an abundance of scientific data, went almost unnoticed.

The further program for exploration of Mars and Venus is expected to include the launching of two more *Mariner* probes in 1969, which are expected to deliver considerably sharper pictures than were possible with *Mariner 4*. While no details of future Russian plans have ever been made available so far, in America the *Voyager* project is already being discussed, which is to entail the double launching of two space vehicles with a single Saturn 5 rocket. The two vehicles are to be put into orbit around Mars and are to send out landing capsules from there. While the probes remaining in orbit are taking measurements of the physical relationships in the vicinity of Mars, in order for instance to make a more precise determination of its magnetic field, the soft-landing capsules are to carry equipment with them not only for the study of the atmosphere and the surface, but also devices which will permit the determination of traces of possible bacterial or other life forms. Whether or not Venus too will be included in the *Voyager* project, as has been strongly advocated in America since the soft landing of the Russian instrument capsule, has yet to be determined, as has in fact the question of whether or not the *Voyager* project as such will be carried out, for it has now been greatly endangered by the cut-back in the NASA budget.

Parallel with these interplanetary spaceflight missions, however, just as has been the case in the past, exploration of interplanetary space in the vicinity of the earth is being carried out in much less spectacular manner with the aid of scientific satellites. All the research activities carried out in relation to this have led to our knowing much more about the matter and the physical phenomena in the solar system between Venus and Mars than we did ten years ago. A glance at a true-to-scale representation of the solar system (Figure 1) shows immediately, though, that only a very limited portion of the entire system is being dealt with here. Besides the nine planets *Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto,* all of which



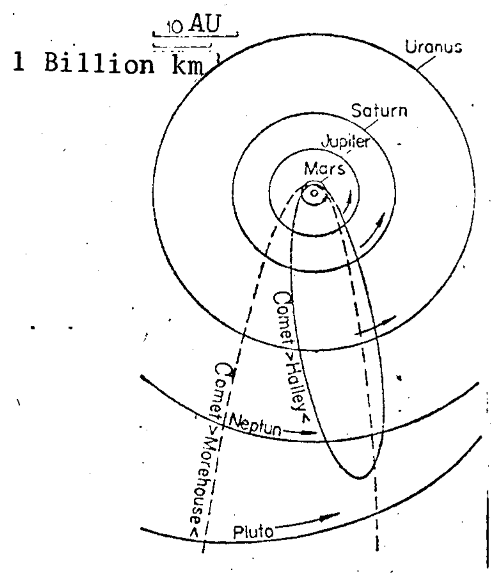


Figure 1a (left). The Inner Portion of the Solar System, from Mercury to Jupiter, with the Asteroid Belt between Mars and Jupiter (Cross-Hatched Area). While the Greater Portion of the Asteroids, Including the Largest, Ceres, Show Nearly Circular Orbits, Others Show Very Marked Eccentricities. The Planetoid Hidalgo thus Goes Out Past the Orbit of Jupiter at Aphelion, While Icarus at Perihelion Plunges into Orbit of Mercury.
Figure 1b (right). The Outer Portion of the Solar System, from Mars to Pluto, with Some of the Comets Shown. (The Asteroid Belt is Not Shown Here.) With the Exception of the Markedly Eccentric Orbit of Pluto, the Orbits of the Planets Do Not Deviate Greatly from the Circular.

(with the exception of the markedly eccentric orbit of Pluto) orbit the sun practically in one plane, the ecliptic, the solar system includes some thousands of very small bodies, the so-called *asteroids*, which for the most part occupy practically circular orbits between Mars and Jupiter (Figure 1a). The planes of their orbits are concentrated for the most part on the ecliptic, though asteroids have also been found with orbits sharply deviating from the ecliptic, and the eccentricity of the orbits of the asteroids also has a much wider spread than that of the planets. In the opinion of many astronomers the planetoids are fragments of a larger heavenly body that was destroyed by a cosmic catastrophe, though these theories require much further study and many more measurements before they can be stated as established facts.

European Research Projects

While the previous results of space research are almost exclusively due to the efforts of the Russians and the Americans, in which, to be sure, Europe- and Japanese researchers have made a decisive contribution through their cooperation, in recent years other nations have decided to participate actively in the exploration of space through the launching of high-altitude research rockets and scientific satellites. The powers of our continent which do not wish to leave this field of scientific endeavor to the two great powers are united in the two European spaceflight organizations ESRO and ELDO.

As the meeting of the Deutsche Gesellschaft für Raketentechnik un Raumfahrt in Munich showed, projects now in the works in Germany have as their aim for the seventies the realization of interplanetary missions in cooperation with NASA by which new scientific territory can be explored, since they will go beyond the space already investigated between Venus and Mars. The discussions below deal primarily with the research and development programs that have been carried out during the past years in relation to these plans.

The foundation for these studies was laid in 1964, when a Franco-German commission which was to check out future ELDO projects further analyzed the Jupiter fly-by project, for which, aside from various technical schools and research institutes, the firms of Bölkow and Erno in Germany and the firm of Sereb in France were making important studies. These studies, which were carried out primarily on the development of carrier rockets, gained increased importance when, on the occasion of Erhard's visit in America, President Johnson suggested a joint German-American effort in the field of interplanetary space flights and spoke of a Jupiter probe.

In the course of the discussion which followed between European and American scientists, the project of a solar probe which was to reach a minimum distance from the sun of 0.3 AU (1 AU = 1 astronomical unit = the distance from the earth to the sun = 150,000,000 km) was envisioned as a German-American task. At the same time a Jupiter mission was planned as a joint project of the American and European space agencies. This was correlated with previous planning efforts in ESRO, and in connection with these the ESRO Council also committed itself in July 1966 to a Jupiter mission in cooperation with NASA. Although in past years great difficulties have arisen in many European countries in finding the means for this task, and the first study for a Jupiter mission has yet to be completed, in Europe, or at least in Germany, the interest in a flight to Jupiter remains, especially since it is hoped that through cooperation with NASA a suitable carrier rocket will be made available, and also since in this way a project can be pursued that cannot be characterized as a simple repetition or imitation of previous Russian or American space undertakings. This may be the point of departure toward a development which will lead to apportioning the horribly expensive tasks to be faced in the field of exploration of the solar system evenly among the industrial nations and will at the same time tend toward such a cooperation as will prohibit the costly duplication of space projects. The picture of a truly scientific competition between Russia and America, which would not only not prohibit but actually require the free flow of scientific information, also belongs in these visions of the future.

"Interplanetary Spaceflight Missions" Symposium in Munich

The symposium held by the Deutsche Gesellschaft für Raketentechnik und Raumfahrt in Munich 7 December 1967 was directed by Prof.Dr. W. Kertz, Prof.Dr. R. Lüst, and Prof.Dr. H. Ruppe. The program included the following projects, which were extraordinarily well documented by comprehensive reports delivered on that occasion:

Dipl.Ing. H. Rosenbauer (Max-Planck-Institut für Physik und Astrophysik, Garching near Munich), "The Solar Wind -- Theories, Measurement Data, and Testing Problems."

Dr. H. Porsche (Study Group for the Exploration of Space, Munich), "Suggestions for Payload for an Interplanetary Probe for Measurements in the Vicinity of the Sun."

Dipl.Ing. D.E. Koelle (Bölkow GmbH, Munich), "Outline Criteria and Alternatives for an Interplanetary Solar Probe."

Dipl.Phys. F.N. Neubauer (Institute of Geophysics and Meteorology of the Technische Hochschule Braunschweig), "The Scientific Tasks of Spaceflight Missions to Jupiter."

Dr. H. Tolle (ERNO-Raumfahrttechnik GmbH, Bremen), "Spaceflight Engineering Considerations in a Jupiter Probe."

W. Kokott (Bölkow GmbH, Munich), "Mission Profiles of an Asteroid Probe."

Dipl.Ing. W. Müller (Bölkow GmbH, Munich), "The Importance of the Swing-By Technique at the Planet Jupiter for Interplanetary Missions."

Dipl.Ing. O. Bschorr (Entwicklungsring Süd [Development Group South], Munich), and Dipl.Ing. A. Leibold (DVL-Institute [Deutsche Versuchsanstalt für Luftfahrt; German Experimental Institute for Air Transport] for Aviation Mechanics, Oberpfaffenhofen), "The Capture and Catapult Capability of Planet-Moon Systems."

Dipl.Ing. H. Wilkesmann (Technische Hochschule Munich), "The Calculation of Two-Impulse Transfer Orbits in the Interplanetary Solar System and the Writing of a Computer Program."

Dipl.Phys. R. Metzger (Bölkow GmbH, Munich), "Electric-Powered Interplanetary Missions."

Because of space considerations the first lecture and the last three lectures cannot be examined in detail here.

The Solar Probe Project

For the German-American solar probe project under consideration, the individual technical planning criteria such as thermal problems, power supply, radio communications, and telemetry, as well as several guidance systems, were discussed by the firm of Bölkow in a preliminary study. On the basis of this the first sketches for a solar probe with triaxial stabilization (ISOS I) and with spin stabilization (ISOS II) could be presented. As Dipl.Ing. D.E. Koelle stated in summary, a spin-stabilized probe shows no essential advantages in regard to technical problems, weight, and development costs, while in his opinion (which was not shared by all participants in the discussion) a triaxially stabilized probe must be given preference with regard to scientific experiments because of its better possibilities for variation and further development.

Planning Criteria

As a basis for study of the project the following two points must be remembered. First, in the fall of 1966 five experiments were decided upon that were to serve for measurement of the magnetic field, of the cosmic radiation of the solar plasma, of the micrometeorites, and of the zodiacal light; these are described in some detail below. It was also found from an analysis of the available carrier rockets that for approaching as close as 0.3 AU to the sun only the *Atlas-Centaur Burner II* combination could be considered. New performance data for the projected improvements up to 1973 showed that a probe of the mass 150 kg could attain an orbit with a perihelion of 0.28 AU. Since there would be no point in not using this increased potential, further studies were based on that proximity to the sun.

The Orbit of the Probe

Since interplanetary orbits that lead away from the plane of the ecliptic are not possible in direct shots with conventional forms of rocket propulsion, and more modern propulsion systems such as ion propulsion have not been adequately tested for use in a large-scale mission, the orbit of the solar probe will certainly lie on the ecliptic. In a coordinate system moving with the earth, the path of the satellite shows up not as an ellipse but as a distorted double eight. In Figure 2 the orbits of a solar probe are shown for varying perihelial distances from 0.26 to 0.30 AU. /10

The total duration of the flight until return to the vicinity of the earth (the flight paths are not closed, in general) will be about one year, the first perihelion being reached after 80 to 100 days and the second after 275 to 295 days. The figure also shows the "blackout zones," in which radio communications will either be strongly interfered with or made quite impossible in flights on the ecliptic of the sun. The first of these is between the inner conjunction with the sun and the first perihelion on the probe's orbit, and lasts only about two to three days. The second blackout zone, in the outer conjunction with the sun, interferes with telemetry on the expected orbits under certain conditions (as, for example, where r_p = 0.30 AU) for more than a month.

Thermal Problems

With close approach to the sun and the consequent increase in the density of solar radiation (by a factor of 12.6 when the sun is approached to within 0.28 AU), great increases in temperature must generally be expected for the solar probe. In principle two methods of temperature control can be used: *active* temperature control, with circulatory cooling systems and the required thermostatic circuits, and *passive* temperature control, in which the temperature is controlled primarily by constant internal heat sources and suitable radiant cooling surfaces. Because of their reliability and low cost, purely passive temperature controls will be used; this is possible in general -- as the studies concerned have shown -- even at a distance of as little as 0.28 AU from the sun.

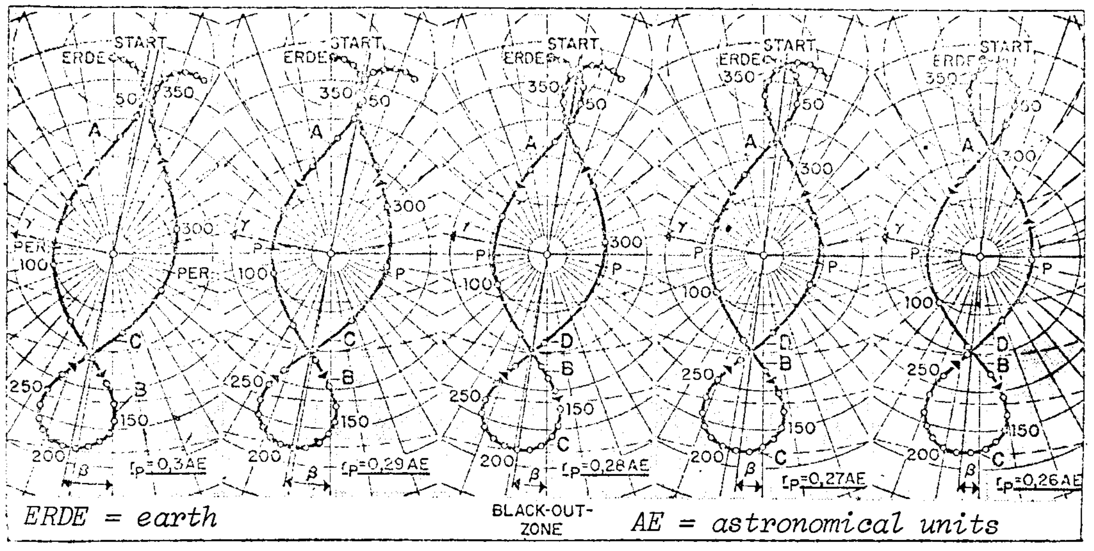


Figure 2. Orbits of an Interplanetary Solar Probe with Perihelial Distances between r_p = 0.26 AU and r_p = 0.30 AU. The Coordinate System is Chosen Such that the Earth Remains in the Same Position. In General the Flight Path is Not Closed and the Angle β Represents the Opening of the Orbit. The "Blackout Zone," Where Because of the Sun No Radio Contact or at Best Only Much Distorted Contact Can Be Achieved from the Probe to the Earth, is Shown by the Shaded Area. Points A, B, C, and D Indicate Passage Through the Center of the Blackout Zone. The Numbers Correlated with the Points on the Circle Denote the Number of Days from the Time of Launching. The Orbit with r_p = 0.28 AU is Distinguished by a Relatively Short Length of Time Spent in the Blackout Zone. (P = perihelion = point nearest the sun.)

In probes whose primary axis is always directed toward the sun (triaxial stabilization), the temperature increase on the face of the probe can be sharply diminished by a heat shield if the face of the probe is conical; indeed, in an approach to 0.2 AU to the sun the temperature of the face of the probe can be kept in the range of 0°C (Figure 3). The temperature problem for a solar probe is therefore reduced to the design of a heat shield, which can certainly be realized technically for a probe to 0.28 AU from the sun, since even with a relatively poor thermal ratio (α/ε = 0.5) the maximal temperature to be expected is only 330°C.

The thermal problems of a spin-stabilized probe, on the other hand, are quite different; first, the rotation reduces the temperature on the surfaces on the order of 150°C, since at any given time only a portion of the cylinder is receiving radiation, and second, since only the surface of the cylinder is available for radiation of the heat generated by the capsule as well as for reradiation of the heat from external sources, an increase in relative temperature cannot be avoided in approaching the sun.

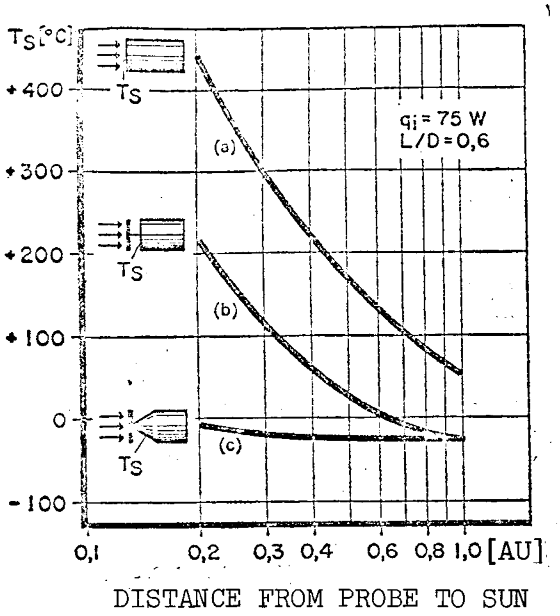


Figure 3. Temperatures on the Face of a Solar Probe as a Function of the Perihelial Distance. a) Without Heat Shield; b) With Circular Face and Heat Shield; c) With Conical Face and Heat Shield. [Commas on chart represent decimals.]

Power Supply

At the present stage of planning, *solar cells*, which convert the sun's radiation into electrical energy, are expected to provide the basis for the power supply for the solar probe. Opinions at the discussion differed as to the possibilities of using isotope generators; in the opinion of the reviewer they have a poorer power-to-weight ratio and will not be ready for use in the next three years.

The *silicon cells* in use today are reliable only up to a temperature of 130°C, and besides that their efficiency decreases as the temperature increases. *Gallium arsenide* cells, which are still useful in higher temperature ranges, are inherently more expensive and their efficiency is relatively limited. Therefore, the increase in temperature of the solar cells with closer approach to the sun must be given considerable attention.

Thermal advantages arise from the fact that in a spin-stabilized probe the sun's radiation is brought to bear only part of the time, but these advantages are counterbalanced by the need for an increased number of cells. Aside from all that, a maximum exterior temperature of less than 130°C can be expected only up to a distance of 0.4 AU, and with closer approach additional measures must be taken -- either the solar cells must be placed on a conical surface, which requires the use of additional surface, or else an active cooling system must be used, which must be paid for by a weight increase and lowered reliability.

The smallest area of solar cells is required when a flat, tiltable surface is used in connection with triaxial stabilization, as has already been done in the American *Nimbus* weather satellites. If only *four discrete angles of incidence* are provided, which are employed depending on the solar radiation, the temperature and the power delivered can be kept more or less constant in an approach to as close as 0.28 AU from the sun (Figure 4).

Another solution to this problem can be found by using three fixed planes of solar cells at different angles to the sun. In the approach to the sun, first the vertical and then the slightly planes fall out due to over-heating, but the third plane of solar cells continues to function well enough at the perihelion to maintain a power supply of 80 watts (Figure 5). The drawback of this method is that after the first perihelion has been passed through, the electrical power dwindles so rapidly that for the rest of the trip the probe is

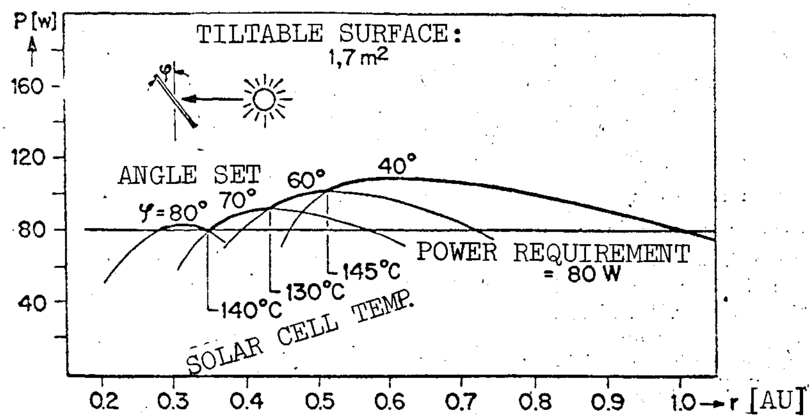


Figure 4. Tilt of Solar Cell Surfaces to Achieve Uniform Temperature and Power Output. The Mean Power Requirement is Assumed to be 80 Watts.

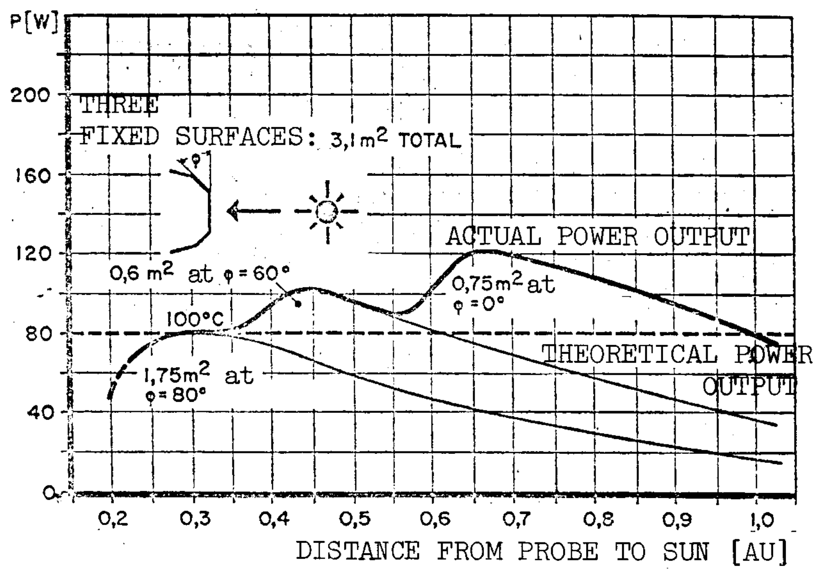


Figure 5. Curve of Power Output for Three Fixed Solar Cell Surfaces set at Angles of 0°, 60°, and 80° During Approach to the Sun. The Total Solar Cell Surface is 3.1 m^2.

hardly able to function.

Radio Communications and Telemetry

Radio communications between solar probe and ground station have three functions to perform: 1) transmission of measurement data from the probe to the earth; 2) transmission of commands to the probe and its instruments; and 3) measurement of the distance from the earth to the probe.

The special nature of radio communications with a solar probe as opposed to those with an ordinary scientific satellite, apart from the enormous maximum distance (about 300 million km) to be covered, lies in the interference of the sun, which is considerable in a large part of the flight path. The data flow from the five experiments planned is expected to be about 15 bits per second. On the realistic assumption that the comprehensive American DSIF (Deep Space Instrumentation Facilities) network will be available to the solar probe four hours a day on the average, a data transmission capability of 90 bits per sec. will be required for the hours of actual transmission, in view of the possibility of data storage. With a broadcast antenna that would require 32 to 58 watts for transmission, but with a flexible directional antenna it could probably be accomplished with only about four watts, though with certain mechanical and operational drawbacks (possible loss of radio communications!). In either case only a small part of the installed capacity is utilized.

Combining a broadcast (fan beam) antenna and a fixed directional antenna might well produce the optimal results in a triaxially stabilized solar probe. Fixed installation of the directional antenna is possible because the earth, during the critical phase of maximum separation from the probe (that is to say, during approximately half the voyage), remains within an angle of ± 10° of the primary axis of the probe (cf. Figure 2). The interference of the sun is somewhat abated when the transmitting capacity of the directional antenna is raised to 10 watts, and this transmission capacity also suffices for transmission of data during the rest of the flight with the fan beam antenna. Moreover, this combination makes it possible to increase the flow of data considerably during the period of blackout, when the probe is in front of, near, or behind the sun, and thus substantially decrease the period of interruption of radio contact (Figure 6). Nevertheless, for the one-year duration of the flight the period

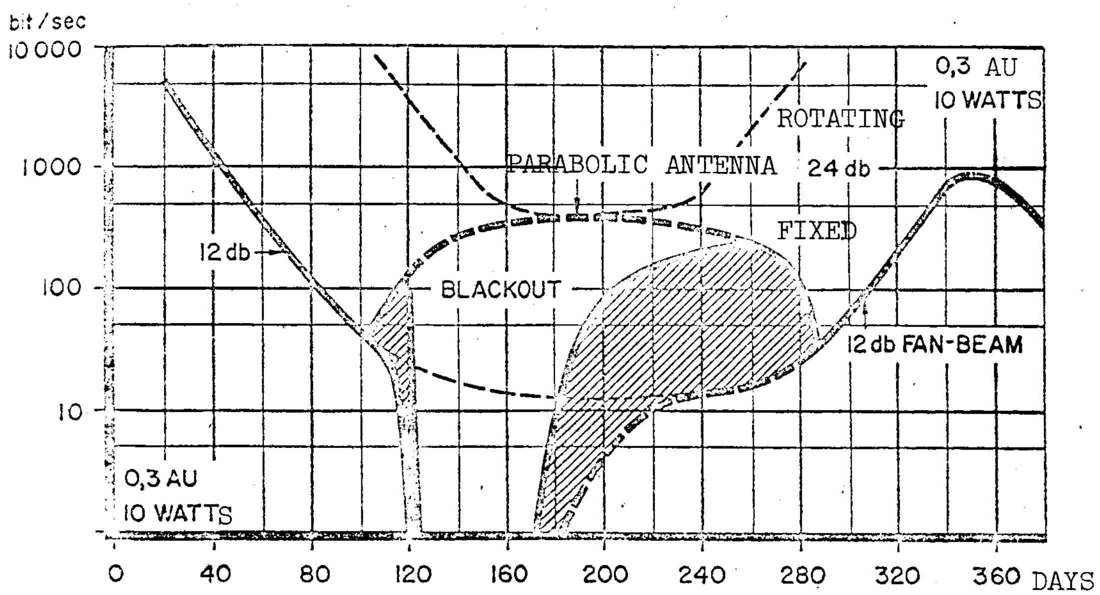


Figure 6. Increase in data flow (shaded area) by combination of a fan beam antenna with a fixed directional antenna in the critical region of blackout. The fan beam antenna has a maximal antenna gain of 12 db, the parabolic antenna 24.

of interruption of radio contact is still approximately 68 days, so that approximately 18% of the measurement data will be lost if no additional means of data storage is provided, as opposed to a loss of approximately 23% to 33% to be expected with the directional antenna alone.

Triaxial or Spin Stabilization

The control of an interplanetary space probe is characterized by the fact that only very limited disturbing influences appear. Thus, for example, the Mars probe *Mariner 4* used only 2 kg of gas for attitude corrections during the entire three-year duration of its flight. For a solar probe, steering maneuvers and course corrections are also unnecessary, so that in principle the control system can be very simple.

Spin stabilization is generally the simplest method, and for that reason has been used in many scientific satellites, such as the *Pioneer* probes, for example. If we remember, though, that in a spin-stabilized probe the primary axis will have to be rotated 90° after the burn-out of the last stage, as will be required by some of the additional equipment, it will be seen that the weight allowed for the control system and the number of subsidiary components might well run as high for a spin-stabilized probe as for a triaxially stabilized probe, -- about 10 kg. Therefore, from the point of view of the control system, there is hardly any difference between the two methods. Other factors, such as the thermal problem, the power supply, and data transmission, show a certain advantage for a triaxially stabilized probe, as can be seen from the foregoing discussion, since this would permit an increased flow of data (with fixed directional antenna) and simpler temperature control through the use of a heat shield. As far as the choice of scientific experiments is concerned, spin stabilization would normally place greater limitations on the scientific instrumentation, since not all test devices will operate while rotating.

In summary it may be observed that while spin stabilization may well lead to simpler solutions for earth satellites, for a solar probe its advantages become more and more limited as the distance from the sun diminishes. At 0.25 to 0.30 AU the limits of the technical feasibility of a spin-stabilized system have been reached, and below 0.20 AU practically the only usable system is a triaxially stabilized system aligned on the sun.

II. Design Projects

Various designs for an interplanetary solar probe have been worked out /11 by the firm of Bölkow, both with spin stabilization and with triaxial stabilization.

The American *Pioneer* space probe may be used as a starting point for all concepts involving spin stabilization, even though it was designed for use at a distance of 0.8 to 1.2 AU from the sun. For a solar probe, however, additional criteria must be considered, especially with regard to thermal stress on the solar cells. The solution chosen for the probe *Isos II* (Figure 7) envisions an insulated ring of solar cells, in which the temperature is limited by the use of reflector surfaces and the main body is separated from the

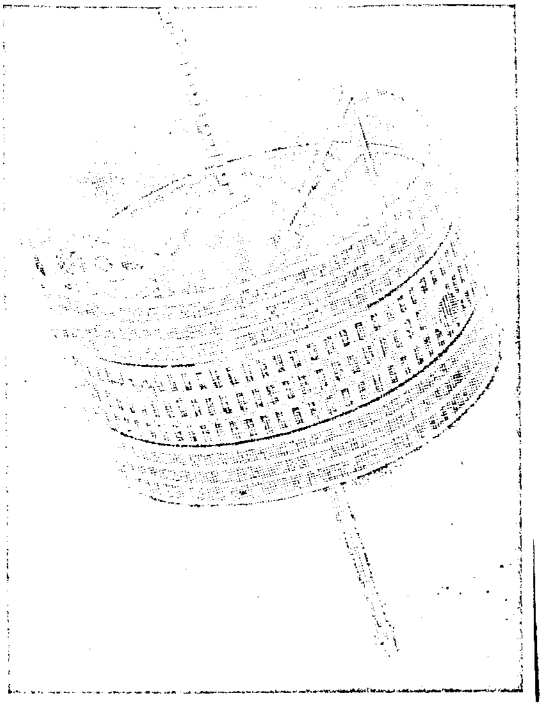


Figure 7. Bölkow Design of a Spin-Stabilized Solar Probe *Isos II A.*

outer surfaces. The optimal setting for the solar cells is with one surface at 90° to the sun, which will lose effectiveness at 0.45 AU from the sun because of overheating, and one surface at 45° to the sun which will still produce enough energy in a closer approach to the sun because of the higher density of solar radiation there. If it is desired to transmit 90 bits per second over a distance of 2 AU, the power supply on board will have to be capable of developing at least 215 watts, and this calls for a surface of 10 m^2. If part of the measurement data are dispensed with, a transmission range of 1.5 AU can be set up, which would limit the demands on the on-board power supply to 143 watts. This assumption was set up as a basis for the development of *Isos II A*. This leads to a body 2.6 m in diameter, 1.5 m in height, and weighing 185 kg, broken down as follows:

Scientific instrumentation	28 kg	Power supply	51 kg
Data processing and storage	15 kg	Body and thermal control	53 kg
Data transmission	14 kg	Reserve	17 kg
Guidance system	7 kg		

Reduction in size and weight is possible only with the use of a flexible directional antenna, as provided for the design of *Isos II B*; in this case the power requirement is still about 63 watts and the mechanical and control outlay is increased, while the reliability of radio communications is decreased.

Isos I C, shown in a cut-away drawing in Figure 8 and as a model in Figure 9, may be regarded as the most promising concept for a triaxially stabilized solar probe. This design shows a large data-transmission capacity provided by two fixed antennas, and as for the solution of the thermal problem, the use of the heat shield and the conical form is extremely simple. Three of the five pieces of apparatus are suitably protected behind the heat shield and offer maximum accessibility. The magnetometer is situated on a beam above the fan beam antenna, while the zodiacal light instrument, which must be protected from stray light, is situated in the center of the probe.

The Scientific Apparatus

After Dipl.Ing. H. Rosenbauer of the Max-Planck-Institut für Physik und Astrophysik had summarized the results of measurements to date and the currently prevailing theories on the solar wind, Dr. H. Porsche of the Arbeitsgemeinschaft für Weltraumforschung explained the scientific objectives set for the

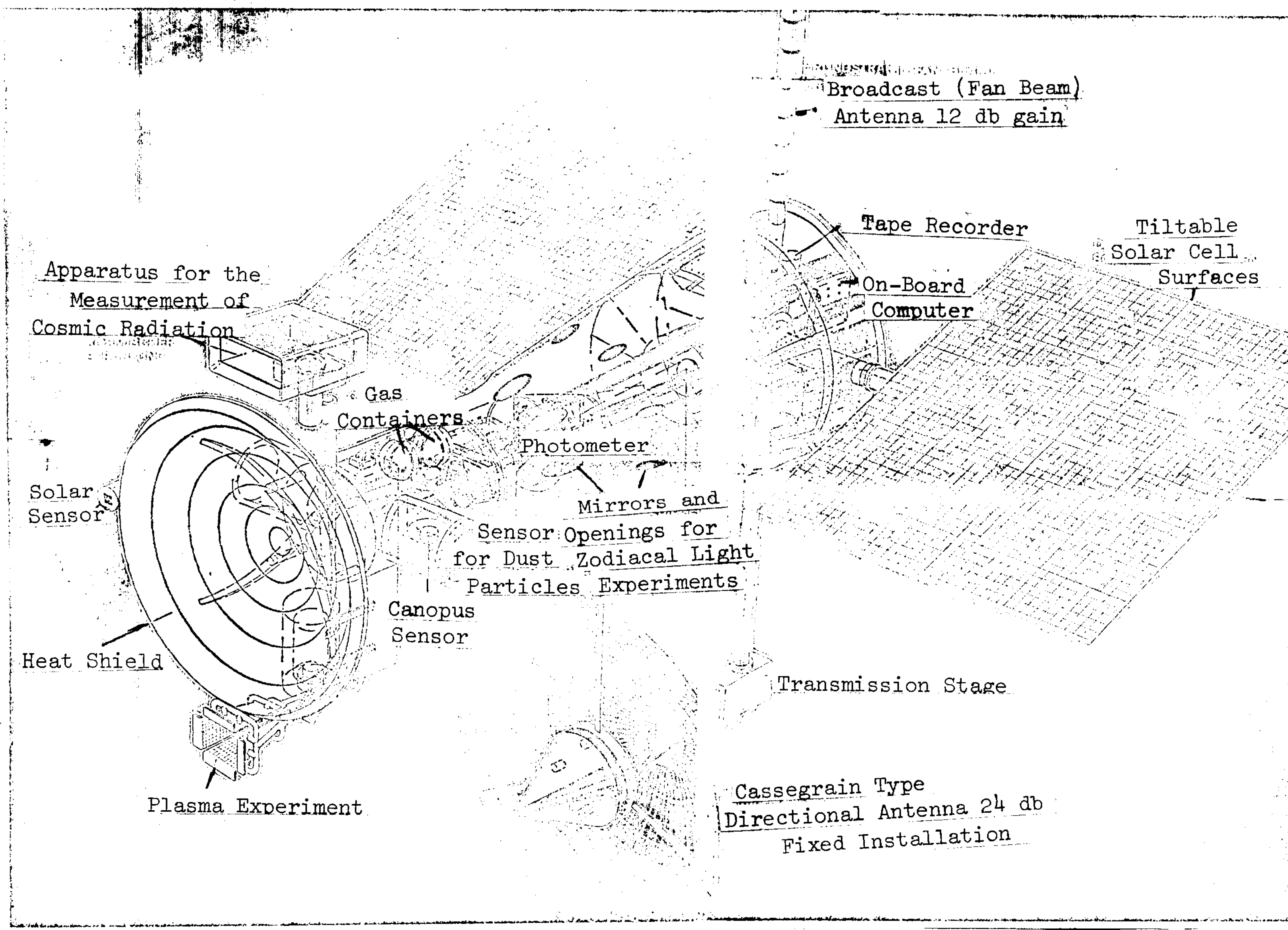


Figure 8. Cut-Away Drawing of the Triaxially Stabilized Solar Probe *Isos I C* with the Experimental Apparatus Installed, and with the Antennas and the Tiltable Solar-Cell Surfaces.

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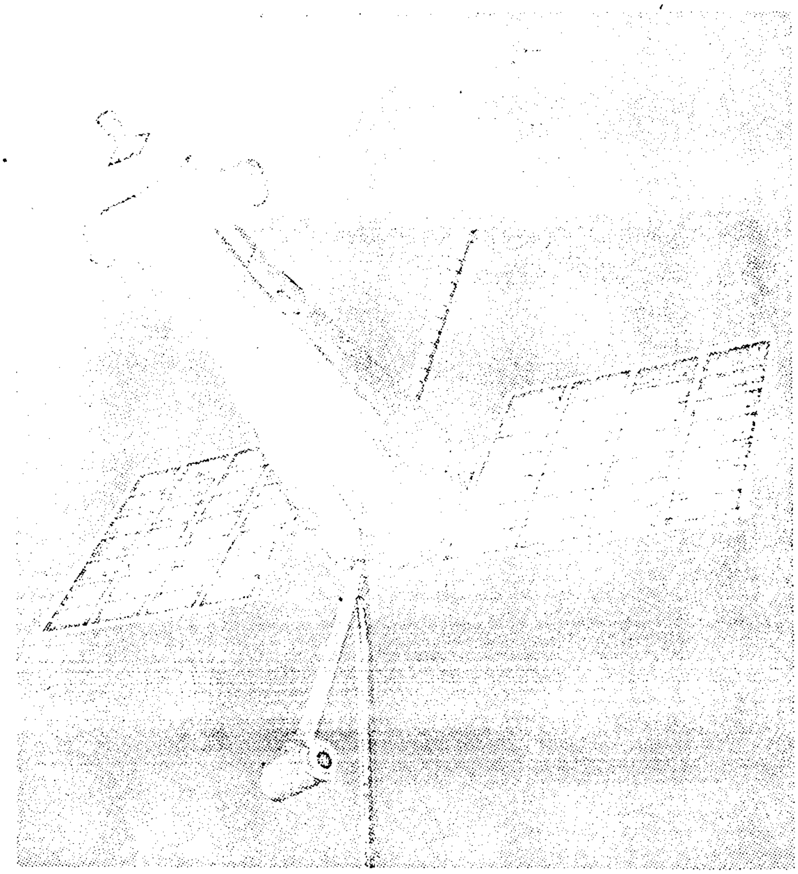


Figure 9. Model of the Triaxially Stabilized Solar Probe *Isos I C*.

solar probe project. Interest is focused on the phenomena whose source is to be found in the sun, i.e., essentially, the wave radiation and corpuscular radiation of the sun. As distinguished from these observations, optical observation of the sun from the solar probe would probably show nothing new.

In the observation of particles a distinction must be made between charged and uncharged particles, as well as between particles of solar origin and those of galactic origin. Of special interest in this respect are the protons and heavy ions of the solar wind and their correlation with solar phenomena and with the interplanetary magnetic field. The conditions of propagation of the solar wind and its properties in the vicinity of the sun have not been sufficiently explored, either. Observation of the high-energy neutrons is very difficult in a space vehicle, but since the density of neutrons to be expected even at the perihelion of the orbit is not very great, failure to take measurements of the neutrons is not of too great importance. On the other hand an experiment concerning micrometeorites should on no account be neglected, since they are of essential importance in any description of interplanetary space.

In the USA as early as 1963 in a NASA report various experiments were discussed that could be carried out by a solar probe in interplanetary space,

Table 1. Selection of Experiments Which are to be Carried Out by the American Solar Probe Sunblazer. *This Project is Being Worked on by an MIT Team.*

Apparatus	Objective	Mass	Power Requirement
1. 100-300 MHz transmitter (simultaneous transmission of housekeeping data)	Working conditions in the corona: 1) Sellmeier formula (refractive index) = electron density 2) Faraday effect = magnetic field 3) Damping	1 kg	10 to 20 w or 500 w/100 MHz 250 w/300 MHz in pulses
2. Electronic analyzer; 2 instruments, 4 directions each, narrow angles	Composition, force, and direction of plasma streams to an accuracy of about 5°. Only ions between 200 and 2500 km/s	3.6 kg	3 watts
3. Electronic analyzer, wide angle	Plasma density as a function of heliocentric distance	2.25 kg	1.5 w
4. 3-axis flux-gate magnetometer	Magnetic field measurements, 0.12 γ to 500 or 1000 γ	2 kg	0.5 w
5. Detector for high-energy particles	1) Dependence of high-energy particles on the magnetic field and on solar activity 2) Search for Li nuclei 3) Comparison of solar and galactic particles	3.4 kg	1.0 w
6. Telescope for charged high-energy particles	Directional distribution of solar particles	0.5 kg	0.5 w
7. 50-400-2000 MHz transmission	See item 1.	2.25 kg	2 w
8. Microphone for micrometeorites	Zodiacal light and F corona	1.8 kg	1 w
9. Ionization chamber for X-rays	Flare monitor	1.4 kg	1 w
10. Semiconductor for particles of medium energy	Range ca. 0.1 kev to 10 Mev	0.9 kg	0.5 w
11. Ly α nucleus photometer	Content and temperature of the neutral gas H	3.2 kg	3 w
12. Zodiacal light photometer	Registers the intensity as a function of the elongation	2.25 kg	1 w

Table 1. (continued)

	Apparatus	Objective	Mass	Power Requirement
13.	VLF noise receiver	Ca. 10 to 100 kHz is to be received	3.6 kg	0.5 w
14.	TV facsimile apparatus	Observation of the far side of the sun for prediction of solar flares	4.5 kg	12 w minimum 2 s at a time
15.	VLF impedance probe	Electron density measurement	0.9 kg	1 w
16.	Neutron detector	0.1 to 100 Mev range	9 kg	1 w
17.	Coincidence telescope for high-energy electrons	Not precisely stated	0.9 kg	0.5 w
18.	Measurement of the charge of the space probe	Charge of the vehicle	1.8 kg	2 w
19.	Telescope for high-energy cosmic rays	Differentiation of solar and galactic rays	3.2 kg	1 w
20.	RF mass spectrometer	Composition of the neutral gas and of the ions in interplanetary space	2.25 kg	5 w

but at that time no concrete plans were made to carry them out. Further NASA studies in later years led to the proposed *Sunblazer* project. The experiments, for the most part suggested by an MIT research team, may be reduced to the twenty problems summarized in Table 1.

The planned German-American solar probe is not so ambitious, and limits itself to the following five experiments:

1. *Plasma Detector to Measure the Number, Energy, and Direction of the Protons and Alpha Particles in the Solar Wind.* No decision has yet been reached as to the choice of measurement systems.

2. *Magnetometer.* Two measurement systems are planned for this: a) Three Förster probes for the three static and slowly variable components of the interplanetary magnetic field. b) An induction-pulse system for sudden changes in the field (e.g. impulse waves of up to 10 kHz).

3. *Detector for High-Energy Particles* in the range from 1 MeV to 1 GeV for protons, from 4 MeV/N to 1 GeV/N for alpha /12
particles, and from 1 to 15 MeV for electrons. The planned measuring instruments are scintillation counters and film counters.

4. *Photometer for the Inner Zodiacal Light.* In the wavelengths around 3500 Å and 5000 Å the intensity of the zodiacal light and the degree of its polarization at an angular distance of 15° and 30° from the center of the sun are to be measured.

5. *Micrometeorite Detector* to register dust particles down to 10^{-15} g (at relative velocities of 10 km/s). The mass and energy of all particles and the chemical composition of heavy particles ($m > 10^{-12}$ g) are to be determined. Data are also to be obtained as to the direction of the particle velocity.

Figure 8 shows how the instrumentation for these experiments is to be installed in the probe *Isos I C*. In addition to the five experiments described above, other suggestions are being discussed, such as a detector for middle-energy electrons in the range between 40 and 150 kev, in which the measuring instrument uses scattering gold foils and semiconductor detectors, as well as an impedometer to measure the electron density in the vicinity of the probe.

A final decision as to the scientific instrumentation of the solar probe cannot be reached until the entire project is cleaned up in cooperation with NASA and correlated with American plans for a solar probe.

III. The Project of a Probe to Jupiter and the Asteroids

Since both the Russians and the Americans have carried out successful flights to Mars and to Venus, it can be expected that sooner or later flights to Jupiter, too, will be realized. This offers Europe the chance to cooperate on an equal basis with the other nations interested in spaceflight on a major project in the course of development. In America just as in Europe the project for a Jupiter flight is only in the planning stage; while projects are being worked on in America for an *"Advanced Planetary Probe"* and a *"Galactic Probe,"* in Germany the firms of Erno-Raumfahrttechnik GmbH and Bölkow have already carried out design studies for a Jupiter probe, which will be discussed in brief below. /13

Jupiter is the largest planet in the solar system, and its mass is twice as great as the mass of all the other planets taken together. Besides that, it shows a number of peculiarities whose scientific investigation would certainly be greatly simplified by a spaceflight mission. In Table 2 some of the most important data known about Jupiter are listed and compared with the corresponding data for the earth.

The scientific value of a Jupiter mission, however, is not limited to the exploration of the planet itself; many other scientific research tasks could be carried out with the Jupiter probe. For one thing, the solar probe mission could be expanded by carrying out a study of the interplanetary plasma at a greater distance from the sun. During the flight through the asteroid belt (see Figure 1) the composition of certain of the large asteroids could be determined as well as the microparticle distribution existing within the belt. Further useful scientific research projects suggest themselves in relation to the twelve moons of Jupiter, about whose composition and origin as yet only hypothetical arguments exist, while exact knowledge about them could be of great importance to the cosmology of the solar system.

Table 2. Comparison of Some Characteristic Data Pertaining to Jupiter and Earth

	Jupiter		Earth	
Mean Distance from the Sun	5.20	AU	1.00	AU
Period of Revolution	11.86	years	1.00	years
Mean Orbital Velocity	13.06	km/h	29.80	km/h
Diameter at the Equator	142,700	km	12,756	km
Oblateness	0.062		0.003	
Mass	1.9×10^{30}	g	6.0×10^{27}	g
Density	1.334	g/cm^3	5.52	g/cm^3
Acceleration Due to Gravity	26.0	m/s^2	9.81	m/s^2
Escape Velocity	61.0	km/s	11.2	km/s
Mean Temperature	∿140	°K	300	°K
Magnetic Field Strength at the Equator	∿ 10	gauss	0.31	gauss

Model of a Jupiter Probe

Quite different criteria must be considered in the design of a Jupiter probe from those for a solar probe. In his report "Spaceflight Engineering Considerations in a Jupiter Probe," Dr. H. Tolle of Erno-Raumfahrttechnik, Bremen, dealt specifically with the problems involved in communications, power supply, determination and maintenance of attitude, and heat economy.

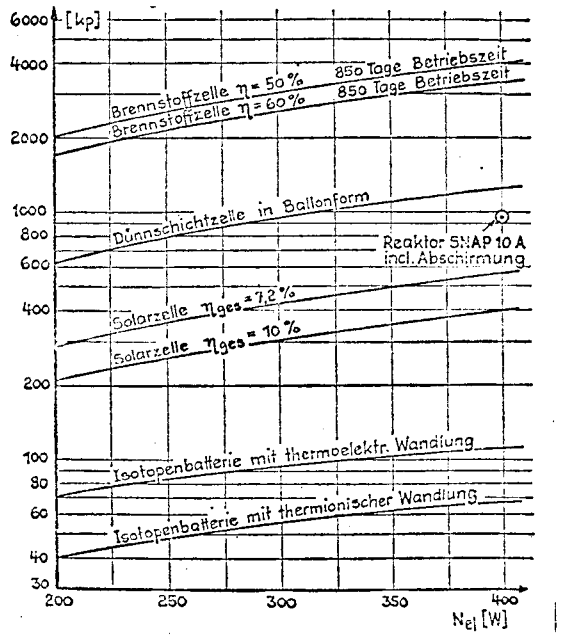
Communications

With regard to the communication of information it must be remembered that the probe, while it is passing Jupiter, will be about 700 million km from the earth, that is about five times as far from the earth as the earth is from the sun, and this means that with the frequencies normally used in interplanetary space flights, free-space damping of the signal will reach almost 280 db. In order to keep the transmitting capacity required on board the probe within manageable limits, the telemetric contact between the earth and the probe will have to emanate from large on-board and ground antennae. For reception on the ground the American DSIF system, whose standard antennae are 25 meters in diameter, will be available, and for special purposes some 63-meter antennae may also be used. The on-board antennae cannot exceed 2.5 meters if they cannot be folded and if carrier rockets of 3.05 meter diameter (*Blue Streak*, *Atlas-Centaur*) are to be used. With a transmission density of 100 bit/s, under optimal conditions (2.5 m on-board antenna and 63 m ground antenna) a transmitting capacity of 33 watts will be required; if only the 25 m antenna of the DSIF are available, or if 0.8 m on-board antennae are used, the energy requirements jump to ten times that. Just for comparison purposes, it should be noted here that the corresponding transmitting capacity of the *Mariner* probes reached a maximum of 10 watts.

Power Supply

For a transmitting capacity of 33 watts, the entire communications unit will have a power requirement of 130 watts. If the power requirements for the scientific apparatus are calculated at 1 watt per kg, an additional power requirement of 100 w will have to be satisfied for the projected instrumentation. Thus the total power supply can be planned for 200 to 300 watts, a peak capacity of 50% above the continuous power output being assumed.

Weight of Power-
Supply Plant



fuel cell η = 50% 850 days useful life
fuel cell η = 60% 850 days useful life

thin plate cell in balloon form

10 ampere SNAP reactor incl. shielding

solar cell η_{tot} = 7.2%
solar cell η_{tot} = 10%

isotope battery with thermoelectric conversion

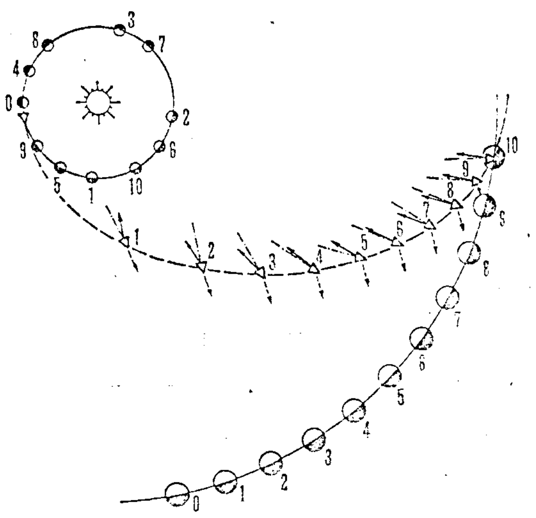
isotope battery with thermionic conversion

Figure 10. Weight Comparison of Various Power-Supply Units for a Jupiter Probe in the Capacity Range Between 200 and 400 Watts.

Figure 10 shows a comparison of the weights of various power plants, with the shielding requirements for the nuclear power plants included. From this it can be seen that isotope batteries, which will use strontium^{90} as the working isotope, show by far the best power/weight ratio. Their superiority to solar cells for this mission stems from the fact that to produce the same amount of power about 25 times as large a surface is required in the vicinity of Jupiter as in the vicinity of the earth. The 7.2% degree of efficiency is derived by considering the radiation influences, protective filters, and incomplete packing of the solar cells; an optimal reduction in these disturbing influences should permit 10% efficiency for the solar cells currently in use. A major improvement over the current ratios could only be brought about, however, by the technical realization of the solar cells now under development, which promise a power/weight ratio five times better than those currently in use. Should this breakthrough actually take place in the next few years, the disadvantages of isotope batteries, whose radiation could falsify the results of the scientific instruments, could be got round by the use of solar cells.

Heat Economy

Since the large on-board antenna should always be aimed at the earth for best transmission of information, it is planned to set the antenna in a fixed installation in the probe and to stabilize the roll axis, i.e. the primary axis of a cylindrical probe, in the direction of the earth. According to current plans, stabilization of the probe is to be ensured by a special interferometer system.



—•—• aimed toward the earth
----→ aimed toward Jupiter
———→ aimed toward the sun

Figure 11. Transfer Orbit of a Jupiter Probe with a Flight Time of about 28 Months. The Different Arrows Indicate the Direction at a Given Time to the Earth, the Sun, and Jupiter.

If we consider the path taken by a Jupiter probe from its launching up to the Jupiter fly-by (Figure 11), we see that the angle of radiation σ of the sun, after starting at a value of -90°, oscillates at ever smaller amplitudes about 0° (Figure 12). According to the planned form of the Jupiter probe (Figure 13), the cylindrical portion, which is very well insulated, is only irradiated at a very great angle of incidence, while for values of $\sigma < \pm 25°$ practically all the sunlight falls on the antenna. This means that after only a tenth of the total duration of the flight, when the distance from the probe just exceeds 1 AU, the warming of the probe by the sun's radiation will always be brought about by the irradiation of the antenna by the sun. It is therefore justifed to reduce the first approximation of the heat economy to the following two extreme cases:

Maximal temperature: axial solar radiation on the antenna in the vicinity of the earth.

Minimal temperature: axial solar radiation on the antenna in the vicinity of Jupiter.

Calculations show that the temperature of the probe can be kept in the range between -15°C and +45°C, if the variations in solar radiation are compensated for by suitably arranged flaps and if the probe itself is insulated on the side facing away from the sun by layers of mylar. The thermal problems can thus be solved by semipassive means.

The Planned Jupiter Probe

One of the first designs for the Jupiter probe planned in Germany is represented in Figure 13. This space vehicle was designed for a scientific payload of 100 kg and will have a total weight of 490 kg. The cylindrical body of the probe, housing the electronic and scientific apparatus, has on the side

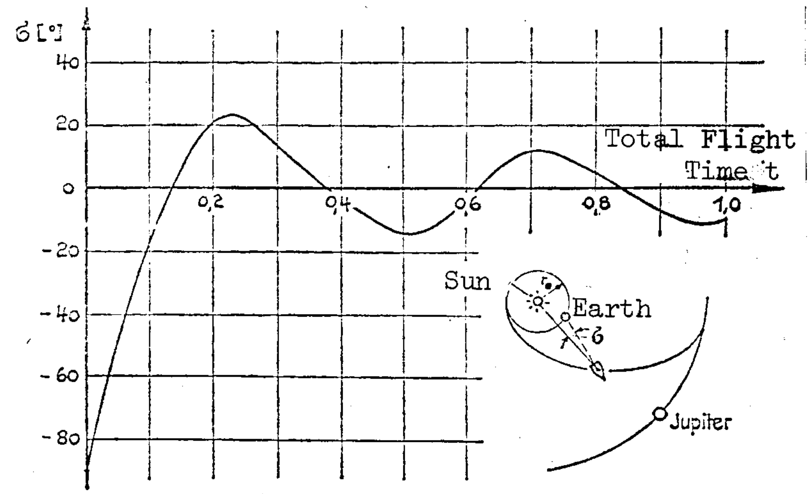


Figure 12. Angle Angle of Incidence of Solar Radiation to the Axis of the Probe. At Launching from the Earth This Angle is 90°; Later it Oscillates with a Frequency of Somewhat More Than One Earth Year Around the Zero Axis.

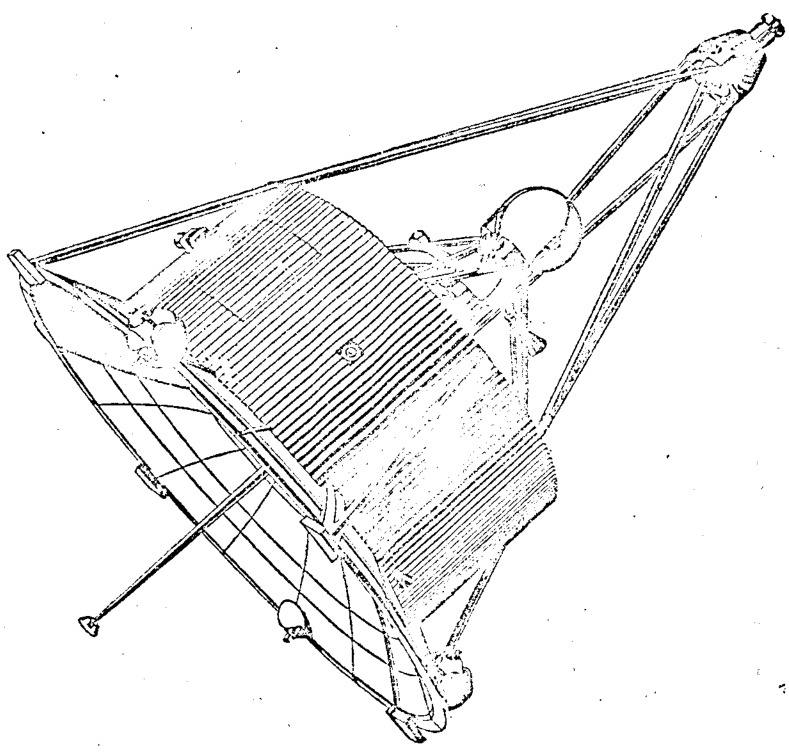


Figure 13. Erno Sketch of a Jupiter Probe. With a Total Weight of 490 kg, it is Designed for a Payload of About 100 kg.

facing the earth a large, fixed, parabolic antenna, and on the opposite side, on a frame at a distance of 2.2 m from the main body of the probe, the isotope battery for power supply. The spheres in the center, which lie at about the center of gravity of the probe, are the containers for mid-course corrections, and the course correction engines are also situated here. On the other hand, the compressed gas jets for attitude corrections are situated so that they will have the greatest possible mechanical advantage. The probe has been planned for an energy-conserving orbit with a flight duration of about 850 days (until Jupiter is reached), in which on the one hand the earth will be as close as possible to the probe at the time of the Jupiter fly-by, while on the other hand the earth will not be directly in line with the sun, which would disturb communications between the earth and the probe. This orbit is shown schematically in Figure 11.

Scientific Tasks of a Jupiter Mission

Dipl.Phys. F.M. Neubauer, of the Institute for Geophysics and Meteorology of the Technische Hochschule Braunschweig, reported on this theme. The scientific experiments of a Jupiter mission are of extraordinary interest to research because Jupiter, after Mars, is the planet for which we have the most extensive prior observations. The interest which has been shown in Jupiter previously is largely due to the fact that Jupiter is the best of the giant planets Jupiter, Saturn, Uranus, and Neptune for observation. Besides this, the observations of radio probes in the decameter and decimeter ranges have made this planet one of the most interesting objects in the solar system. The experiments which could be carried out on a Jupiter mission can be roughly classified in the following four categories:

Magnetic field, magnetosphere, and ionosphere,

Ambient atmosphere,

Planetary interior, and

Moons and small bodies in the vicinity of Jupiter

Only the first two of these will be explored below.

Radio Waves and the Magnetic Field

Jupiter is the only planet besides the earth for which it has been possible to demonstrate the existence of a radiation belt and of a magnetic field brought about by interaction with the solar wind. Our present knowledge of these phenomena has been obtained from observations and measurement of the radio waves in the decameter and decimeter ranges. While the decimeter radiation between 6 cm and 100 cm is nearly independent of wavelength and is linearly polarized to about 30%, the decameter radiation below 43 MHz reaches a peak at 18 MHz and is interrupted for minutes or hours by radio storms which are themselves the results of outbursts which last from fractions of a second to some minutes. According to current theories the magnetic field of Jupiter has a dipole moment of 5×10^{30} gauss/cm^3, which forms an angle of 10° with the axis of rotation. That would produce a magnetosphere with a magnetopausal distance

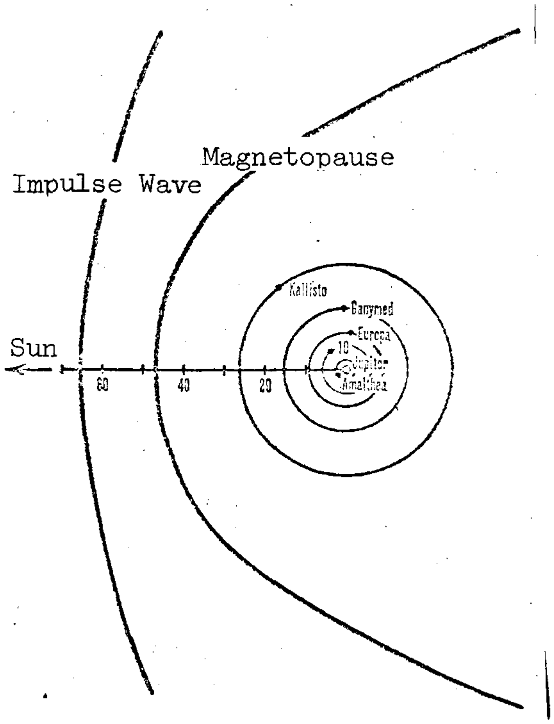


Figure 14. Jupiter and its Satellites. Of the Twelve Moons of Jupiter Only the Four Largest (Callisto, Ganymede, Europa, and Amalthea) are Shown. Because of the Magnetic Field Demonstrated for Jupiter, an Impulse Wave Forms in the Solar Wind as in the Case of the Earth; the Minimal Distance of the Magnetopause at the Subsolar Point from the Surface of the Planet is Currently Believed to be About 50 Jupiter Radii.

at the subsolar point of 50 radii of Jupiter (R_J = 71,350 km), as is shown in Figure 14. Within 3.5 R_J of the center of Jupiter there is a radiation belt containing relativistic electrons with energies of the order of magnitude of several MeV. The ionosphere shows an electron concentration of between 10^5 and 10^6 per cm^3.

The picture of the vicinity of Jupiter sketched here is still rather uncertain, though. A more exact knowledge of the magnetosphere of Jupiter might, in comparison with the earth's magnetosphere, yield valuable keys to various as yet unknown mechanisms of the magnetic field of our own planet. In addition a better understanding of decameter radiation and its relationship to solar activity might make Jupiter into a permanent space probe providing us with information about the interplanetary plasma.

For this reason a Jupiter mission (or even better, a series of consecutive missions) should carry instrumentation for measuring the magnetic field within the magnetopause to just above the surface of the planet, though this can be done only in the most rudimentary way with a fly-by probe; a substantially better determination could be made by an orbiter of high inclination and with a very limited perigeal altitude and a predetermined eccentricity, with which a good spatial coverage could be ensured. A further task consists in the measurement of the energy spectra of electrons between 10 kev and 50 Mev in altitudes below 3.5 R_J. The altitude profile of the thermal plasma is of interest for an understanding of the decameter radiation; in addition, indirect indications may be obtained concerning photodissociation and photoionization processes and concerning the structure of the neutral gas content at ionospheric altitudes.

The Atmosphere of Jupiter

This cycle of problems includes the determination of the temperature distribution of the neutral atmosphere, the chemical composition of the trace substances, and consequently all questions posed in connection with the possibility of the existence of living organisms on Jupiter. The general circulation of the atmosphere of Jupiter is also of the greatest interest, particularly to the atmospheric physicist.

Optical observations of Jupiter show bands and stripes parallel to the equator, which belong to the various layers of the atmosphere (Figure 15). The various zones rotate at speeds dependent on their width and show various colors in photographs; often more or less long-lasting spots and structures show up. The most striking detail of Jupiter is the Great Red Spot, which has been observed continuously for 150 years and extends over an area of 13,000 × 40,000 km.

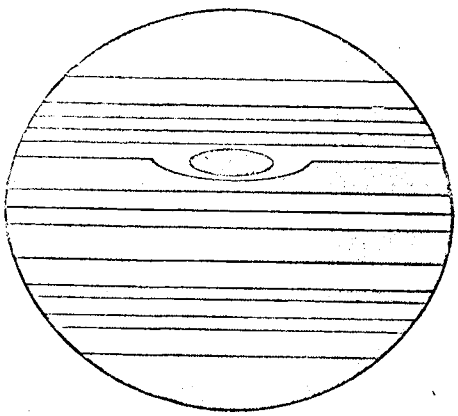


Figure 15. Bands and Stripes of Jupiter as They Can Be Observed in the Optical Wavelength Range from the Earth. A Characteristic Feature of Jupiter is the "Great Red Spot," Which Has an Extent of Some Hundreds of Millions of Square Kilometers.

Cosmogonical considerations as well as theoretical analyses of the escape velocities of the gases in question lead to the belief that the major components of Jupiter's atmosphere are helium and molecular hydrogen. Opinions differ almost by an order of magnitude as to the amount of hydrogen. Therefore determination of the vertical distribution of hydrogen and helium may be regarded as the most important problem concerning the neutral atmosphere. The primary experiment being considered for this purpose deals with the degree of overcast, and will produce a vertical profile of the refractive power of the atmosphere. To determine the hydrogen content spectroscopic measurements are necessary that will provide exact data on the molecular bands of hydrogen at 8,150 Å. For helium other methods must be used, since in the lower atmosphere it absorbs only UV radiations.

An important matter in connection with the structural composition of the atmosphere is its energy economy, in which the portion of the energy flow stemming from the interior and from the surface of the planet represents an as yet unknown value. In order to measure this, the infrared spectrum must be determined for all wavelengths at moderate dispersion. The energy flow from the interior can then be deduced by comparing the incoming radiation with the outgoing radiation. The atmospheric dynamics are also closely related to the energy economy, and additional television pictures in the infrared and optical domains with crude resolution are planned to determine them. The cloud and vapor properties require polarized measurements. Trace substances can be determined by spectroanalysis in the long wavelengths. On the nightside measurements of possible polar light and nightsky light are useful. For study of the atmosphere below the clouds the microwave domain could be used, but interference by the decimeter radiation would then have to be taken into account.

The use of an instrument capsule is also planned for some later date, which would be sent down through the atmosphere of Jupiter by some suitable means and could carry out a large part of the measurements listed above quite simply.

Scientific Experiments in the Asteroid Belt

Any planetary space probe, and therefore any Jupiter mission, will undertake to carry out measurements during the interplanetary flight on the way to its target, in order to provide the optimal scientific yield and certainty of success. Therefore on a flight to Jupiter the exploration of the asteroid belt lying between Mars and Jupiter (see Figure 1) will certainly be given a great deal of attention.

The asteroids occupy a special place among the bodies of the solar system. They range from the size of an average planetary moon to the diameter of a fleck of dust, and their orbits lie for the most part in an area of space where, according to cosmogonical and statistical studies, there should be another large planet. Whether the formation of this planet was prevented by the influence of neighboring Jupiter or whether an already existing heavenly body disintegrated into a large number of smaller bodies remains as unexplained today as the evident relationship between the asteroids on the one hand and the comets, meteor swarms, and other small bodies on the other hand. Besides the scientific importance of exploration of the special rôle of the asteroids in the harmony of the solar system, an exact knowledge of the meteorite density to be expected between Mars and Jupiter is of great importance to the planning of spaceflight missions to the outer planets.

In his discussion of the "Mission Profile for an Asteroid Probe," Wolfgang Kokott of the firm of Bölkow GmbH first gave a résumé of the present state of our knowledge of the asteroids, and proceeded from there to the scientific experiments which could be carried out with an asteroid probe. Basically, three types of mission are possible:

A. Fly-through mission through the asteroid belt,

B. Fly-by of one or more of the major asteroids, and

C. Landing on one of the major asteroids.

For all three types of mission the following studies are of general interest:

I. Determination of the distribution of the asteroids according to size, weight, number, orbital elements, heliocentric distance, length, and width; formulation of groupings through the determination of the mass and velocity vectors of a statistical sampling of objects.

II. Study of the form, surface structure, interior structure, and thermal and electric properties of the asteroids.

III. Study of the chemical, magnetic, mineralogical, and nuclear chemical properties of the asteroids.

For missions of types B or C, which have specific major asteriods as their targets, in addition to II and III the following studies also apply:

IV. Determination of the size, mass, density, composition, and period of rotation of the target asteroid(s) by optical, radar, and celestial mechanical methods.

V. Determination of the values listed above in II and II through direct observation, and of rotation and inertial properties by the methods of spherical astronomy (C).

VI. Carrying out the studies in I above (type C) from the surface of the asteroid, especially when the asteroid in question has sufficient eccentricity of orbit to permit the exploration of a sufficiently large portion of the asteroid belt. In all cases are to be considered the standard measurements of magnetic fields and interstellar plasma, which can attain exceptional significance in the asteroid belt because of the possible influences of the material there on interplanetary phenomena.

The tasks briefly presented here and their introduction in their entirety could be decisive for clarifying the following essential problems:

a) Age, origin and development of the asteroids;

b) Similar or different origin of the small bodies in the solar system (asteroids, small satellites, comets, dust, etc.);

c) Decision on the various comet theories and clarification of the origin of various kinds of meteorites;

d) Cosmogomy of the solar system, especially the distribution of the chemical elements.

Proposed Timetable

Table III shows a possible timetable for exploration of the asteroid belt and Jupiter by means of space probes. It has been assumed that the asteroid probes would proceed in a logical order according to the degree of technological difficulty at the time of their accomplishment and that they and the projected Jupiter missions would be mutually complementary. The timetable shown seems particularly sensible, since in any case of basic minimum of scientific knowledge concerning the asteroid belt will be the basis of all spaceflight missions beyond Mars. Since, moreover, the asteroid belt poses many problems of the highest scientific interest, particularly in the cosmogony and general physics of the solar system, it seems expedient that the time-point X for the first asteroid mission not be set too late; the earliest launching date for this program could be in the beginning of the seventies. The exact planning depends, of course, on general economic considerations not dealt with here, and particularly on spaceflight projects not correlated with the outer solar system.

Table III. Timetable for Asteroid Missions and Jupiter Missions.

Year	*Asteroid Missions*	*Jupiter Missions*
X	Fast fly-through (Jupiter transfer orbit)	
$X + 3$		Jupiter probe (fly-by)
$X + 5$	Slow fly-through, perhaps with flight past one of the larger asteroids	
$X + 7$		Jupiter probe with secondary missions
$X + 10$	Landing on one of the larger asteroids	Landing on one of the moons of Jupiter

In general, in future plans for space probes care should be taken that the first missions in each case not only yield results of general scientific value, but also produce measurements that simplify the optimal planning of later projects. Over and above the special asteroid missions planned, conventional meteorite counters as well as devices for recording microasteroids optically and by radar will become standard equipment for future probes beyond the orbit of Mars. This cannot, however, completely replace a systematic exploration of the asteroid belt by missions specifically planned for that purpose from the beginning, at least for the next two decades.

IV. Use of the Swing-By Technique for Interplanetary Missions

The swing-by technique means, in general, the planned use of the gravitational forces of heavenly bodies to change the course of passing artificial spaceflight devices. In the American literature the terms "gravity term," "gravity assist," and "gravity deflection" also appear for this procedure.

While the work presented by Dipl.Ing. O. Bschorr and Dipl.Ing. A. Seibold thoroughly discussed the capture and catapult capacities of planet moon systems and generally studied the effectiveness of fly-by maneuvers past planetary moons, the lecture by Dipl.Ing. W. Müller on "The Importance of the Swing-By Technique at the Planet Jupiter for Interplanetary Missions" presented a summary of several publications from German and American sources in which many cases had been calculated for practical applications.

Several cases are known to science in which the orbits of comets have been changed greatly by the gravitational field of a large planet. The additional force can have either an accelerating effect, in which case the body in question is driven into the outer solar system, or a braking effect, so that it proceeds into the inner solar system. Such effects have also been observable in planetary missions carried out in the past. The *Mariner* Venus probe launched 14 June 1967 was supposed to pass Venus at a distance of 3200 km after approximately 3½ months' flight time. The plan for the transfer orbit and the proximity was that the probe would undergo a change in direction due to the gravitational field of Venus, which would bring it closer to the sun than would be possible without the Venus fly-by. In a free flight without passing Venus, the probe would have reached a perihelion of 0.72 AU. Because of the Venus fly-by which occurred at a distance of 3968 km on 19 October, the probe will reach a perihelion of 0.58 AU. This mission can therefore be termed the first successful application of the swing-by technique.

Physical Explanation of the Process

Exact determination of interplanetary free flight orbits of space probes requires the solution of a multiple-body problem. The number of bodies to be considered depends on the nature of the planned flight. For example, for a direct Jupiter mission at least the masses of the earth, sun, Jupiter, and the probe would have to be considered, of which, of course, the mass of the probe could be disregarded. The planning and systematic choice of transfer orbits for a given mission are of course simplified by rigorous solutions of the two-body problem, which also yield good starting values for exact calculations. A Jupiter transfer orbit can thus be approximatively broken down into the domains:

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probe-earth, probe-sun, and Jupiter-probe. Three symmetrical gravitational potentials are thus encountered in succession. Within the individual spheres of activity the gravity of the respective central body is considerably greater than that of the others, for which reason the individual portions of the orbit represent conic sections. The heliocentric phase is generally an ellipse, while the planetocentric phases are characterized by hyperbolae. The boundary conditions obtaining during the entry into and exit from planetary spheres of activity can be derived by vectorially subtracting the heliocentric velocity of the planet from the heliocentric velocity of the probe. The relationship of the probe to the target planet can best be illustrated by the representations in Figure 16, where the two cases of acceleration and deceleration of the probe have been sketched. The points *E* represent the entry of the probe into the sphere of activity of the planet in the figure, and the points *A* indicate its exit from that sphere. In the case shown in Figure 16 above, the rate of

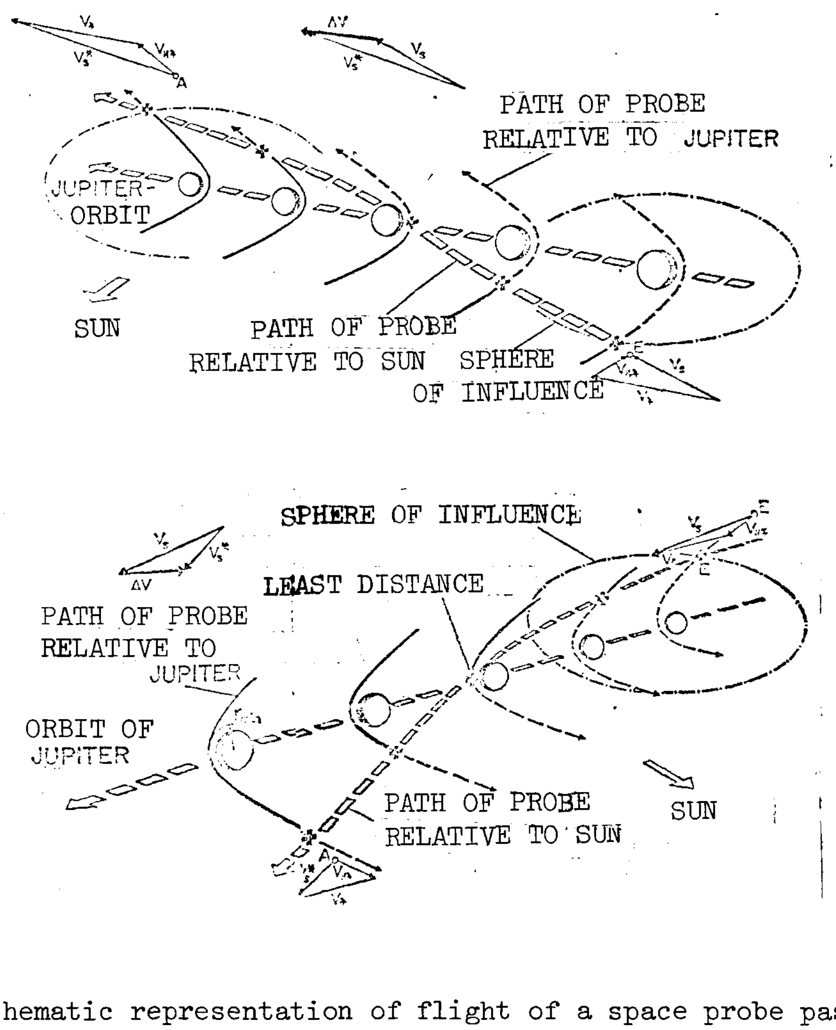

Figure 16. Schematic representation of flight of a space probe past Jupiter. Above: The probe is accelerated by the gravitational potential of Jupiter; the heliocentric velocity of the probe is greater upon exit from the sphere of influence of the planet (point A) than at its exit (point E). Below: The probe is slowed down by the gravitational field of Jupiter; the fly-by takes place in such a way that at the moment of shortest distance between probe and planet the planet is moving in the direction toward the probe.

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heliocentric velocity is greater at exit than it was at entry; the probe has been accelerated by the gravity of Jupiter. In Figure 16 below, the relationship is reversed; the probe has been slowed down. The Jovicentric velocity at entry and exit can be derived from the velocity vector diagrams. From these vector diagrams it can be seen that in the case of acceleration the kinetic energy of the probe is increased from the heliocentric viewpoint, while in the case of deceleration it is decreased. Since the total energy in the system sun-Jupiter-probe represented by the Keplerian orbits of Jupiter and the probe must remain constant, the energy of Jupiter must change simultaneously because of the change in the energy of the probe. In consequence of the great mass of the planet in comparison to that of the probe, however, this change is imperceptibly small.

In the interest of simplicity, Figure 16 shows only the ratios for a two-dimensional fly-by. In general, the angle of the plane of the orbit to the ecliptic can also be changed by a swing-by maneuver.

The amount and direction of the velocity of the probe when it leaves the sphere of influence of the target planet are dependent on the following values:

The velocity vector at the entry into the sphere of activity;

The place of entry of the probe into the sphere of activity, with reference to a system of coordinates with its origin at the center of the target planet; and

The mass and consequently the gravitational constant of the planet.

The gravitational potential of the planet has the greatest importance of all these parameters.

For determining whether a planet is particularly suited for swing-by maneuvers, the maximal energy change of interplanetary transfer orbits ΔE_{max} and the maximal velocity change ΔV_{max} are found to be usable data. The corresponding figures for all the planets in the solar system have been compiled in Table IV. These values may be derived by the following simple formulas:

$$\Delta E_{max} = V_p \cdot \Delta V_{max} \qquad \Delta V_{max} = \sqrt{\frac{k_p}{r_{min}}}$$

(k_p: gravitational constant of the planet; r_{min}: minimum distance from the center of the planet). ΔV is the vectorial difference of the heliocentric velocity of the probe at entry into and exit from the sphere of influence of the planet. ΔE is the difference in the kinetic energy of the probe in the same two cases. ΔV_{max} in this case equals the orbital velocity of a satellite of the planet at the same distance as the apex of the fly-by parabola. The maximal values were calculated for a pericentric distance of one planetary radius. For reasons of safety, these orbits, of course, will never be attained, and this leads immediately to a sharp reduction in the maximum attainable values of ΔV and ΔE. As an example of this, Figure 17 shows ΔV_{max} and ΔE_{max} as functions of the pericentric distance of the swing-by hyperbola at the planet Jupiter.

The values listed in Table IV for the perihelion and aphelion of the conic sections which characterize the orbit before the swing-by maneuver at the four larger outer planets, which produce the greatest changes in velocity and

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Table IV. Maximal Variation of Velocity and Energy in the Gravitational Field of the Planets, with Additional Indication of the Corresponding Alteration of the Orbital Elements in Swing-By. The Order Chosen Here Corresponds to the Maximal Changes in Energy Caused by the Planets. The Last Two Columns Give the Data for the Change in Velocity and the Duration of Hohmann Transfers.

Planet	Mass (Earth = 1)	Orbital Velocity (km/s)	ΔE_{max} (km^2/s^2)	ΔV_{max} (km/s)	Perihelion *Before Swing-By* (AU)	Aphelion *Before Swing-By* (AU)	Perihelion *After Swing-By* (AU)	Aphelion *After Swing-By* (AU)	Hohmann Transfer ΔV (km/s)	Hohmann Transfer Flight Time (Days)
Jupiter	318.4	13.1	583.7	42.6	0.59	∞	3.30	∞	10.8	997
Saturn	95.22	9.7	261.7	25.7	0.31	∞	6.22	∞	10.4	2,209
Venus	0.815	35.1	255.2	7.2	0.47	0.77	0.68	1.25	4.8	146
Earth	1	29.8	239.4	7.9	0.58	1.09	0.92	2.12		
Mercury	0.053	47.9	173.7	3.0	0.31	0.42	0.31	0.53	1.63	106
Uranus	14.55	6.8	107.6	15.1	0.03	∞	13.00	∞	9.9	5,853
Mars	0.167	24.1	95.5	3.6	1.16	1.51	1.34	2.40	3.4	259
Neptune	17.23	5.4	91.9	16.4	3.26	∞	19.86	∞	7.6	11,174
Pluto	0.900	4.7	42.1	6.9	3.66	100.09	23.85	∞	5.9	16.650

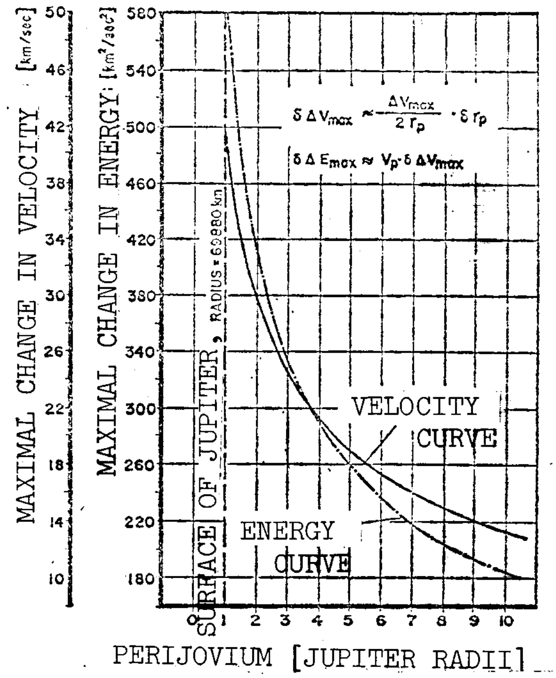

Figure 17. Dependence of the Maximal Change in Velocity and Energy on the Pericentric Distance of the Swing-By Hyperbola Around Jupiter. The Figures Given in Table IV Refer to Perihelial Distances of One Planetary Radius; the Graph Above Shows the Sharp Decline with Greater Pericentric Distance of the Hyperbola.

energy, show that the transfer orbits for these planets already constitute escape hyperbolas for our solar system even before the approach to these planets. For that reason the data for the practical case of a direct connection (*Hohmann ellipse*) are given for all planets in the last two columns of Table IV; the relevant transfer times are also of interest in this connection.

Use of the Gravitational Field of Jupiter for Interplanetary Missions

Use of the swing-by technique at Jupiter permits the following spaceflight missions to enter the realm of the possible during the next few decades:

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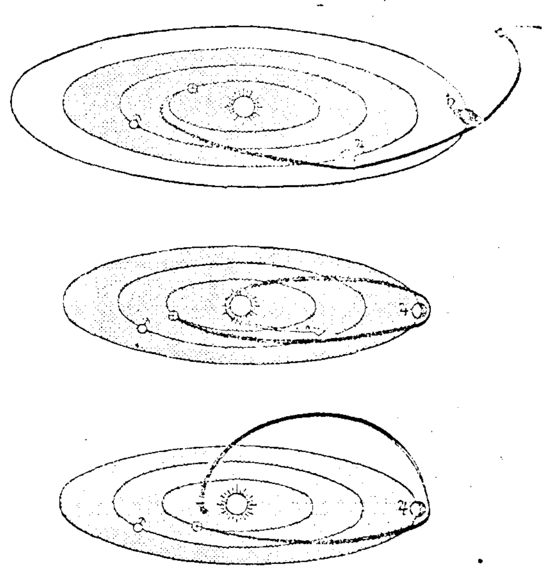

Figure 18. Schematic Representation of Various Possible Uses of the Swing-By Technique at Jupiter: a) Exploration of the Outer Solar System; b) Study of the Sun at Short Distance (<0.1 AU) and Low Heliographic Latitude; c) Exploration of Execliptic Space and of Solar Phenomena in High Heliographic Latitudes.

A. *Objectives in the Transjovian Space of the Solar System:*

Exploration of the outer planets (individual missions);

Mission to the outer planets with one space vehicle (grand tour);

Exploration of the marginal areas of the solar system (cometary cloud).

B. *Objectives in the Cisjovian Space of the Solar System:*

Exploration of solar phenomena on the ecliptic in close proximity to the sun;

Exploration of the sun outside the ecliptic (high heliographic latitudes);

Exploration of the execliptic space of the inner solar system (asteroid mission); and

Exploration of the short-period comets.

Figure 18 shows a schematic view of the orbit profiles of these missions. While the presentation by W. Müller gave a summary of all the most important results of the analytical studies of interplanetary missions from the available literature, we are limiting ourselves here to a rather detailed discussion of the Saturn mission, a triple swing-by mission, indirect solar probes (within and without the ecliptic), and a discussion of the possibilities of a rendezvous constellation with a comet to be achieved by a swing-by maneuver at Jupiter.

Saturn Missions

The next target after Jupiter will be the planet Saturn, which has won the interest of the scientist primarily because of its limited density of 0.7 g/cm^3 and its great oblateness of 10%.

Various calculations have shown that swing-by missions to Saturn are possible with a minimal launching velocity of 9.25 km/s; the closest approach to Jupiter in that case would be 1.5 radii of Jupiter. The total flight time, to be sure, is very high -- almost five years. The most effective direct mission to Saturn in 1977 would have a flight duration of about four years. For this a hyperbolic launching velocity of about 11.5 km/s would be necessary. If the orbit of the probe approaches to within a distance of 10 planetary radii of the center of Jupiter, a flight of the same duration would require about 9.5 km/s. Thus the considerable amount of about 2 km/s is saved by the use of the swing-by method, and this greatly reduces the demands made on the rockets. For extremely short-duration flights, however, direct missions are at least as good as swing-by missions.

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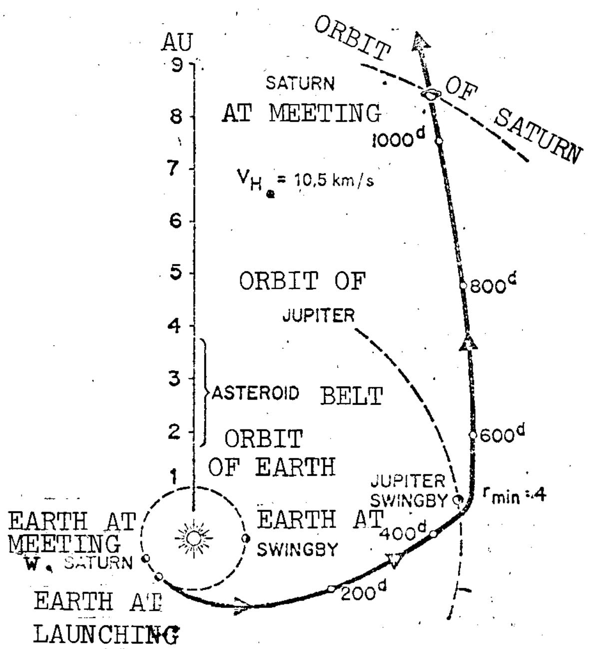

Figure 19. Saturn Mission with Jupiter Swing-By, Calculated for an Ideal Solar System. The Duration of the Flight is 1072 Days.

Figure 19 shows the theoretical course of a transfer orbit. The launching takes place in September 1977. The initial geocentric velocity required is 10.5 km/s. Jupiter is passed at a distance of three planetary radii. The heliocentric velocity is increased vectorially to 18.7 km/s. A sharp bend in the undisturbed orbit from earth to Jupiter can be discerned. Saturn is reached after a total flight duration of 1072 days. Other favorable launching schedules occur in July or August 1976 and in October 1978.

Changes of Direction in Several Gravitational Fields

Calculations for spaceflight missions to the planets of the outer solar system show that the average flight durations to be expected are from three to twelve years, while the initial velocities required are of the order of magnitude of 10 km/s. This calls for an extraordinarily high scientific and technical outlay for such missions. It seems sensible for this reason to combine the possible individual missions to the outer planets into a single mission on the basis of the velocity gains to be derived from the gravitational fields of Jupiter, Saturn, and Uranus. Studies of several consecutive changes of course of a probe by means of the gravitational forces of the outer planets have shown that a whole class of such missions is actually possible in the second half of the seventies.

Figure 20 shows the essential results of this work. The path of a mission is shown here that would have to be launched on 14 September 1977. The characteristic initial velocity is 9.9 km/s. After approximately two years the probe reaches Jupiter, where the planned course change occurs at a distance of 12 Jupiter radii from the center of mass. Saturn is reached after another two years, on 12 December 1981. The probe must pass this planet on the nightside at a distance of only 3.4 Saturn radii. As will be seen, the trajectory undergoes the greatest change at Saturn. A scant five years later, on 31 July 1986, Uranus is passed, on the dayside, at a distance of 6 Uranus radii. The rest of the mission lasts another four years, so that the planet Neptune is reached on 23 May 1990. The entire mission thus requires approximately 12 years and 8 months. The propellant requirements and flight duration are about the same as would be required for an individual mission to Neptune. If we assume that the swing-by maneuvers can be accomplished within the limit of permissible error, this kind of triple swing-by maneuver offers the possibility of studying the four major planets of the outer solar system with a single space vehicle.

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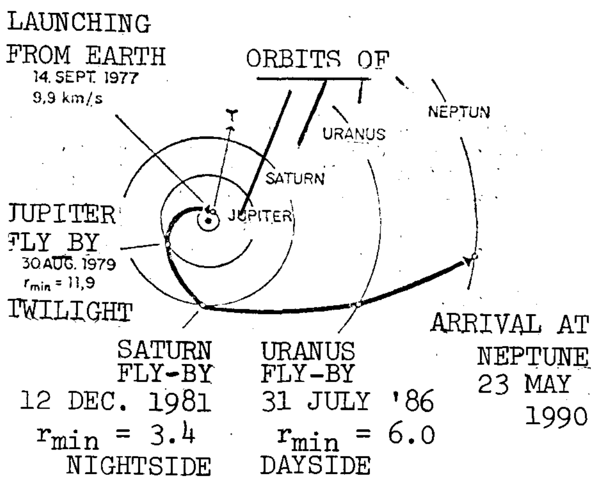

Figure 20. Threefold Swing-By Mission (Grand Tour) into the Outer Solar System, the Gravitational Potentials of Jupiter, Saturn, and Uranus Being Used in Turn in Order to Reach Neptune After Thirteen Years' Flight Time. A Favorable Constellation of the Planets for Such a Flight Has Been Calculated for 14 September 1977; If That Date is Missed it Will Be Years Before Similarly Favorable Conditions Occur Again.

While the second half of the seventies provides ample opportunities for launching individual missions to the outer planets of the solar system, the possible launching dates for a triple swing-by mission are much more thinly strewn. According to Flandro's data, a mission of this sort could be launched on 7 October 1978, but the initial velocity would have to be 11 km/s.

Solar Probes

In order to study the inner solar system and particularly the immediate vicinity of the sun more closely, besides direct missions the possibility of redirecting a probe around Jupiter in such a way that it is brought into close proximity to the sun, either inside or outside the plane of the ecliptic, may be resorted to. Figure 21 shows the relationship between the flight duration, power requirement, and first perihelion for ecliptical solar probes that make use of the gravitational potential of Jupiter to decelerate the probe. While of course the flight duration of the swing-by mission is a great deal longer than that of a direct mission, passing Jupiter permits a far closer approach to the sun than is possible in direct missions with the initial velocities that can be achieved today. If, for instance, a perihelial distance of 0.02 AU is to be achieved by a direct mission, an initial velocity of 24 km/s must be attained, while this value could be reduced to approximately 10.5 km/s by making use of the gravitational field of Jupiter, a reduction of about 56%.

The difference is even greater when execliptic orbits are desired. For direct missions, regardless of the perihelial distance desired, an initial velocity of 30 km/s must be attained if the plane of the orbit is to be normal to the ecliptic. The only available recourse here is the use of the gravitational potential of Jupiter. In order to attain the desired inclination of the plane of the orbit of the probe by the Jupiter fly-by, the hyperbolic escape velocity of the probe must be greater than or equal to the heliocentric velocity of Jupiter at the time of entry into Jupiter's sphere of influence. This is the case only when the passage time from the earth to Jupiter is 450 days or less. Numerous studies were carried out by R. Metzger to clarify the relationship between the orbital parameters of the undisturbed transfer orbits from the earth to Jupiter and the parameters of the orbits after the swing-by maneuvers. By way of example, Figure 22 presents a perspective illustration of the orbital

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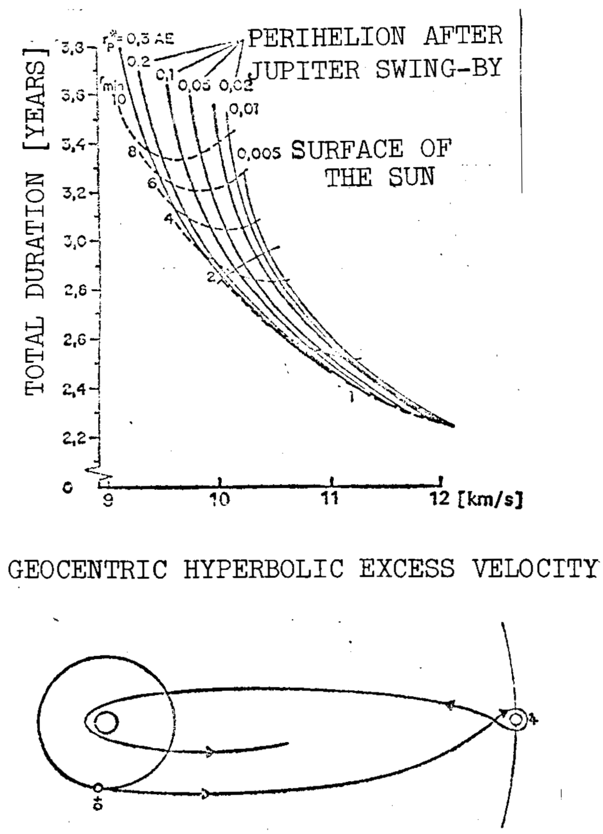

Figure 21. Orbital Parameters of an Indirect Ecliptical Solar Mission with Jupiter Swing-By. The Orbit from the Earth Around Jupiter to the Sun, Running in the Ecliptic, is Schematically Represented Below.

path of a mission that could be launched on 26 June 1975. The necessary initial velocity is 11 km/s, since the transfer orbit earth-Jupiter lies only slightly off the ecliptic. The probe reaches a proximity of 7 planetary radii from Jupiter 450 days later. This throws the probe 90° off the plane of the ecliptic, and the new perihelion that comes about will be at a distance of 0.045 AU from the sun. The entire mission from launching to perihelion will last 3.14 years. The time spent in the asteroid belt will be about 200 days on the trip to Jupiter from the earth and another 200 days on the way from Jupiter to the sun.

In the case of execliptic missions for solar research the swing-by maneuver must be carried out in such a way that the probe is sharply decelerated. This greatly reduces the aphelion and the short semi-axis as well as the perihelion, as can be seen from Figure 22. It follows from this, however, that such missions are unsuited to exploration of the high execliptical space of the inner solar system. For the exploration of targets at great distances from the ecliptic, such as meteor swarms, the plasma, and the magnetic field, methods must be found that will throw the probe 90° off the ecliptic but will not have so strong a braking effect. A great number of studies have already been carried out on this point.

Cometary Missions

An extraordinarily interesting subject in the exploration of space is represented by the comets, and certainly the most interesting single target among them for the next twenty years is Halley's Comet, whose last perihelion was observed in 1910 and whose return is predicted for 1986. This comet is singled out ahead of the others because of its shorter perihelial distance (0.59 AU), its size (absolute luminance M_0 = 4.6), and its retrograde orbit. For a direct fly-by mission launched in January or July 1985 the relative velocity of the probe to the comet would between 60 and 70 km/s. A rendez-vous therefore appears impossible with the present capacity of chemical rocket propulsion systems.

Here again the use of the swing-by at Jupiter offers a way out (Figure 23). According to calculations, the launching would take place from the earth

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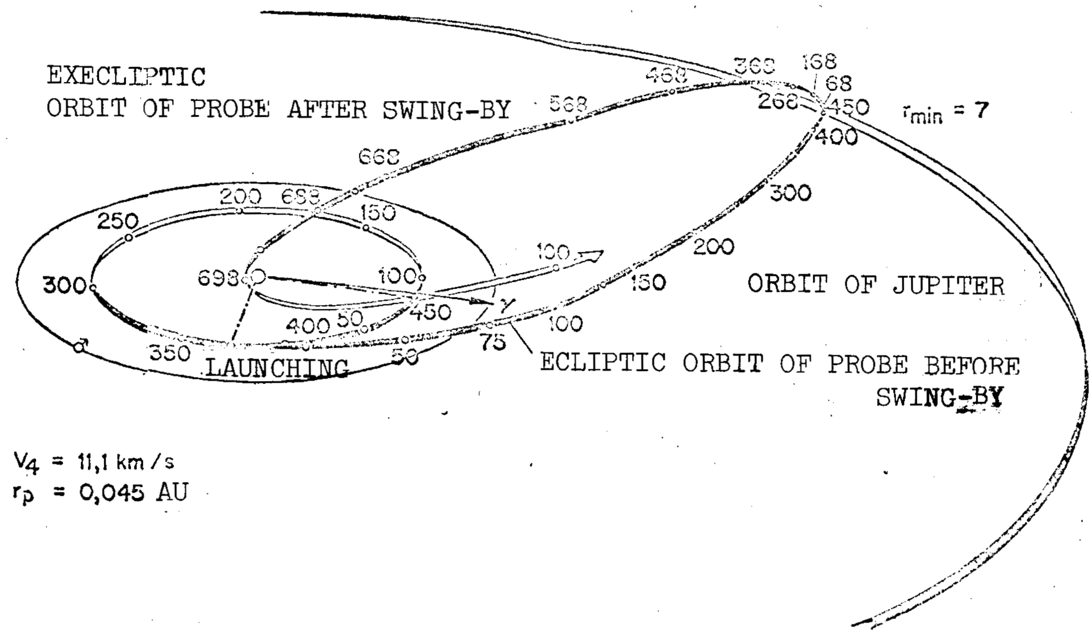

Figure 22. Orbit of an Execliptical Solar Probe After a Jupiter Swing-By. The Probe is Thrown out of the Plane of the Ecliptic by the Change of Direction at Jupiter.

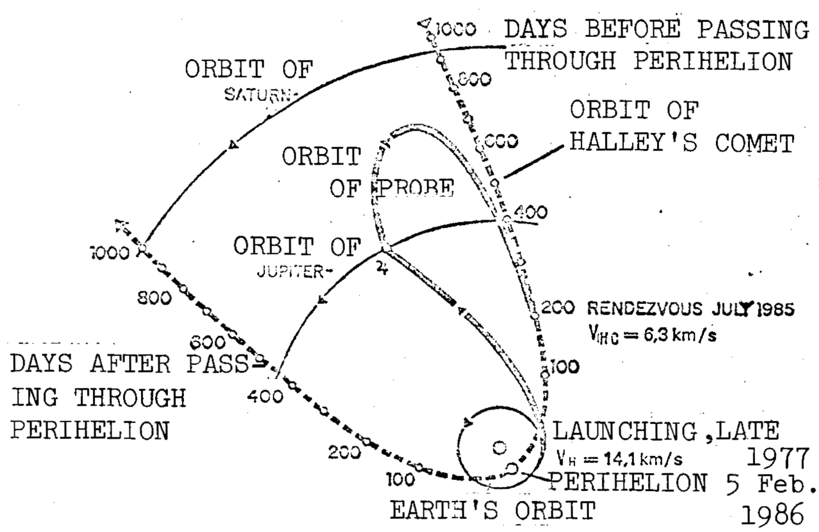

Figure 23. Rendez-Vous of a Probe with Halley's Comet After Flight Around Jupiter. By the Swing-By Maneuver at Jupiter the Probe is Catapulted 160° Out of the Ecliptic and is Thus Given a Retrograde Orbital Direction, Like That of the Comet Itself. At the Meeting Point, Where the Comet Overtakes the Probe, the Relative Velocity of the Probe with Respect to the Comet is About 6.3 km/s; for a Real Rendez-Vous, in Which the Two Heavenly Bodies Fly Side by Side for Some Time, the Propulsion System of the Probe, Controlled from the Earth, Would Therefore Have to Generate a Change of Velocity of That Amount.

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at the end of 1977. The power requirement corresponds to an initial velocity of about 14 km/s. After a relatively short flight time to Jupiter, the probe would fly in an orbit on a plane at an angle of about 160° from the ecliptic into the inner solar system. In this way the direction of the probe's travel becomes retrograde in the astronomical sense, or the same as that of the comet. The meeting of the two heavenly bodies takes place in July 1985, approximately 200 days before the perihelion of the comet is reached, at a distance of about 3.8 AU from the sun. In order to realize an effective rendez-vous with the comet, so that the two heavenly bodies fly along side by side at the same velocity, the probe would have to increase its own heliocentric velocity at this time. At the precalculated point in its orbit the comet's heliocentric velocity will be approximately 23 km/s. The relative velocity, which would have to be overcome by the propulsion system of the probe, amounts to about 6.3 km/s, or only about 10% of that required for a direct mission.

Problems of the Swing-By Technique

The importance of the swing-by technique for the exploration of the solar system can be clearly seen from the examples given above. The great reduction in power requirements of orbits into the outer solar system must be seen as a great advantage of this technique over direct missions to the same targets. While the use of the gravitational field of Jupiter has a favorable effect on the flight duration of missions to the outer solar system, missions into the inner solar system are sometimes made considerably longer in duration. That the probe must pass through the asteroid belt twice for missions into the inner solar system must be counted as a further disadvantage, since the danger of collision with small bodies is thus doubled.

The necessary exactitude of the orbit may well present the greatest problems, however. The greatest demands on the course correction system will be made by secondary missions into the outer solar system, and of course especially by multiple swing-by missions. Even small changes in the heliocentric velocity vectors shortly before the jovicentric phase will bring about considerable variations in the orbital parameters. Although exact calculations for the fuel requirements for these course corrections in the missions discussed are not yet known, it would be safe to state that the weight of these masses of fuel is not the critical factor, but rather the necessity of igniting the course-correcting engines more often than for the missions carried out thus far. This is of the greatest importance for targets in transjovian space, primarily because small errors in the velocity vectors have a telling effect on target exactitude due to the great distances involved. The precision of the orbits for solar probes with Jupiter swing-by will be less problematical. Although the value of the initial velocity will have a great effect on the resulting perihelion, errors in the injection rate up to a certain point will be of less seriousness, since it will have little effect on the experiments whether the probe approaches to within 0.1 AU or 0.05 AU of the sun.

The necessity for an adequate degree of redundancy to ensure a high level of reliability follows from the technical problems outlined above. The necessary useful loads can of course be launched with the *Saturn 5*, and the *Saturn 1 B* with suitable upper stages can be used for such interplanetary missions, as

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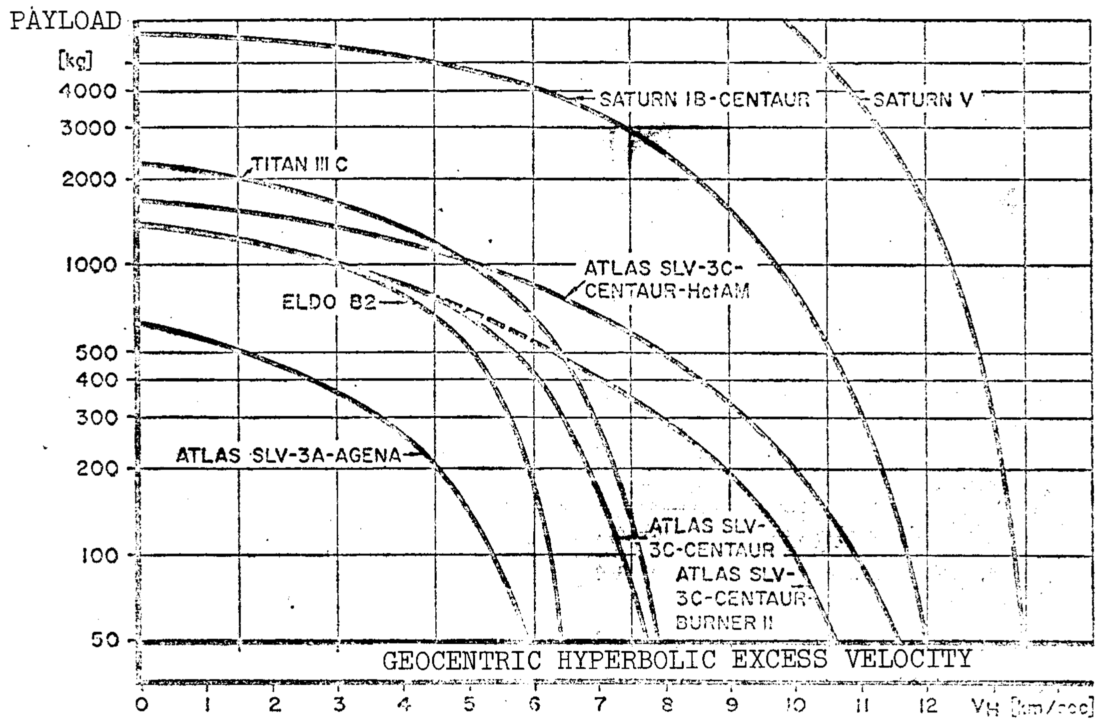

Figure 24. Estimate of Useful Loads of Carrier Rockets for Interplanetary Missions.

is shown by an appraisal of the useful loads of various carrier rockets for interplanetary missions (Figure 24).

Documentation

At the symposium all the lectures were documented in an exemplary manner by comprehensive reports. It is thanks to this fact that the present article presents a summary of the most important reports, from which most of the pictures and diagrams used are also taken. Rather than list the bibliography here, therefore, we refer the reader to the titles of the lectures, which are listed in the first part of this article [page 5].

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